

AL/EQ-TR-1994-0041



## CROSSFLOW AIR STRIPPING WITH CATALYTIC OXIDATION

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THIS QUALITY INSPECTED

September 1994

19950518 030

Final Technical Report for Period October 1, 1990 - September 1990

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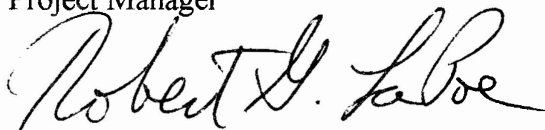
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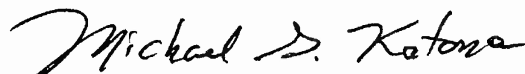
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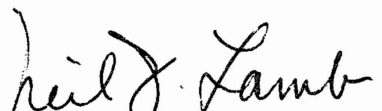
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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-1302, and to the Office of Management and Budget, Paperwork Reduction Project (074-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 30, 1994		3. REPORT TYPE AND DATES COVERED Final, October 1, 1990 to September 30, 1994
4. TITLE AND SUBTITLE Crossflow Air Stripping with Catalytic Oxidation			5. FUNDING NUMBERS F08635-90-C-0064	
6. AUTHOR(S) B.C. Kim, A.R. Gavaskar, S.K. Ong, S.H. Rosansky, C.A. Cummings, C.L. Criner, A.J. Pollack, and E.H. Drescher				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Battelle 505 King Avenue Columbus, OH 43201			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) HQ AL/EQW-OL 139 Barnes Drive, Suite 2 Tyndall AFB, FL 32403-5000			10. SPONSORING / MONITORING AGENCY REPORT NUMBER AL/EQ-TR-1994-0041	
11. SUPPLEMENTARY NOTES Project Officer: Maj. Mark H. Smith (904) 283-6126 DSN 523-6126				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A novel air stripping technique was tested on a pilot scale at Dover Air Force Base. Groundwater contaminated with 1,2-dichloroethane was subjected to air stripping in two towers: the novel crossflow tower and the conventional countercurrent tower. The crossflow tower was found to require higher airflow rates but much lower pressure drops to effect the same removal efficiency. The airstream from the towers was directed into bench-scale and pilot-scale commercial catalytic units. An innovative photocatalytic unit also was tested. Five of the six catalysts tested performed well. Air stripping in conjunction with catalytic oxidation was found to be a good technique for remediation of groundwater containing low levels of organics. However, the crossflow air stripper did not offer any cost advantages over conventional counterflow air stripping.				
14. SUBJECT TERMS crossflow air stripping, catalytic oxidation, groundwater, water treatment			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

## PREFACE

This report was prepared by Battelle, 505 King Avenue, Columbus, OH 43201-2693 under Contract No. F08635-90-C-0064 for the Environics Directorate, Armstrong Laboratory, AL/EQW, Tyndall Air Force Base, FL 32403-5323.

This final report describes the pilot-scale design and testing of an innovative air-stripping technique. The crossflow air stripper and a conventional countercurrent air stripper were used to remediate groundwater contaminated with organics at Dover Air Force Base. The airstream from the stripper was treated using several different catalytic oxidation units.

The authors wish to acknowledge the technical support provided by Milton Beck, Bob Wikso, Tom Dunsmore, and Mick Mikula of Dover Air Force Base.

The work was performed between October 1, 1990 and September 30, 1994. The AL/EQW technical project officers were Capt Edward Marchand (during the initial stage of the project) and Maj Mark H. Smith (during the later stage of the project).

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## **EXECUTIVE SUMMARY**

### **A. OBJECTIVE**

The overall objective of this project was to design and field-demonstrate crossflow air stripping and catalytic oxidation as cost-effective treatment technologies for cleanup of contaminated groundwater. Specific objectives of this demonstration were to compare the volatile organic compound (VOC) removal efficiency of the crossflow air stripper to that of a conventional countercurrent air stripper. Included in this study was the field evaluation of the performance of several types of catalytic oxidation units in destroying halogenated hydrocarbons in the off-gas from the air strippers.

### **B. BACKGROUND**

This study was conducted to provide a credible database to be used by the U.S. Air Force in evaluating innovative air stripping and catalytic oxidation technologies with potential technical and economic advantages. On several Air Force sites, spills, leaks, and seepages have resulted in contamination of groundwater with VOCs, including chlorinated compounds. Air stripping, rather than carbon adsorption, is becoming the preferred process for removing VOCs from groundwater at several sites because of the cost advantages. Air stripping towers typically are designed in a countercurrent arrangement. The crossflow air stripping technology was developed by Louisiana State University (LSU). In the crossflow arrangement, a number of partial baffles are spaced evenly throughout the tower, and the packing is placed in the center of the tower cross section between the baffles. Previous bench-scale experiments by LSU had shown that this arrangement reduces the gas velocity and reduces the pressure drop across the tower, creating a potential for reduced energy cost for the air blower. Also, higher air-to-water ratios were achieved by the researchers without causing flooding than were possible with conventional strippers. What was needed was an evaluation of the crossflow air stripping and catalytic oxidation technologies under field conditions, at a scale that would be suitable for use in designing a full-scale application.

### **C. SCOPE**

In this study, the crossflow air stripping concept was tested under field conditions at Dover Air Force Base (AFB), in order to evaluate its applicability, especially for compounds with low Henry's Law constant that are difficult to strip. Several commercial catalysts for treating the airstream from air stripping are available from vendors, but their effectiveness claims had to be verified under field conditions. Other experimental and innovative catalysts were tested to evaluate advances in oxidation technology. Recommendations for scaleup and design of large-scale towers also were made.

### **D. METHODOLOGY**

To evaluate the new technologies, two towers were designed, assembled, and operated in parallel under identical test conditions at Dover AFB. One tower was a conventional countercurrent air stripping (CCAS) tower and the other was a crossflow air stripping (CFAS) tower. The CFAS tower was designed such that it had the same packed height (17 feet) and the same packed volume as the CCAS tower. Each tower was capable of handling up to 50 gpm of water flow. The air leaving the two stripping towers was combined and sent to several conventional and innovative catalysts, that were arranged in a parallel configuration. All the catalysts were tested in small bench-scale units

(less than 1 scfm air), except for the innovative photocatalytic unit which was tested in a pilot unit at approximately 50 scfm. The rest of the air from the towers was discharged directly to the ambient.

Water and air samples were collected before and after air stripping to evaluate tower performance. Air samples were collected before and after each catalyst to evaluate catalyst performance. These samples were analyzed in an on-site laboratory. Because initial analysis indicated that VOC levels in the groundwater were lower than expected, 1,2 dichloroethane (DCA) was spiked to a level of 1 ppm into the inlet water in order to achieve meaningful results. Thus, DCA was the only contaminant present at any significant level in the water, and most of the evaluation is based on its removal and destruction. DCA was selected because it has a low Henry's Law constant, which makes it difficult to strip.

## **E. TEST DESCRIPTION**

Two series of tests were conducted. First, a preliminary test was conducted during August to November, 1993. Later, an extended test was conducted during May to July, 1994. During the preliminary test the stripping towers and catalytic units were evaluated under a wide variety of test conditions. For the air stripping towers, the variables evaluated were water and air loadings, air-to-water ratio, and baffle configuration. For the catalytic oxidation units, the variables evaluated were catalyst temperature and space velocity (residence time). The objective of the preliminary test was to arrive at a set of optimum operating conditions for the towers and catalysts.

During the extended test, the towers and the catalytic units were operated continuously, at the optimum conditions determined during the preliminary test, for 10 weeks to evaluate any variability of performance over time. The photocatalytic unit was tested only during the extended test.

Sodium citrate was added as a sequestering agent during the preliminary test, but was eliminated during the extended test because it was contributing to microbial growth.

## **F. RESULTS**

The crossflow tower was capable of the same stripping efficiency as the conventional countercurrent tower, but at a higher air-to-water ratio. However, the higher air-to-water ratio required in the CFAS tower is achieved at a pressure drop that is an order of magnitude lower than in the CCAS tower. During the extended test, both towers (a CCAS tower and an equivalently sized CFAS tower) consistently demonstrated 95 percent stripping efficiency of DCA at air-to-water ratios of 60 (CCAS) and 94 (CFAS). The corresponding pressure drops were 2.0 (CCAS) and 0.2 inches of water in 17 feet of packing. Higher stripping efficiencies (greater than 95 percent) were obtained in both towers at selected test conditions.

The most widely used correlation for estimating mass transfer coefficient, the Onda's correlation, was found to be overpredicting the coefficient in both countercurrent and crossflow towers. This is consistent with other air stripping studies that have found the correlation to overpredict when there is a significant gas-phase resistance to mass transfer.

Several commercial catalysts are available that can effectively treat chlorinated organics in the high-humidity airstreams expected from air stripping operations. In this study, bench-scale fixed-bed catalysts manufactured by University of Akron, Haldor Topsoe A/S, Allied Signal, Inc., and Salem Engelhard, Inc. demonstrated high destruction efficiencies at the recommended test conditions (800 to

880°F). Over 99 percent destruction efficiency of DCA was achieved under selected conditions. A new fixed-bed catalyst, supplied by a commercial vendor, also was studied at the bench scale, but was found to be still in the developmental stage requiring further optimization.

An innovative new photocatalytic oxidation technology, manufactured by KSE, Inc., was tested at pilot scale during the extended test. This unit incorporates a combination of a new catalyst and UV light to oxidize chlorinated organics. This unit performed consistently at the design condition of 95 percent destruction efficiency of DCA during the extended test period. Approximately 99 percent destruction efficiency was achieved under selected test conditions. This catalyst operates at lower temperatures compared with conventional catalysts, resulting in lower operating costs.

## G. CONCLUSIONS

The CFAS tower has the potential to strip compounds with low Henry's Law constant (e.g., DCA) with the same efficiency as a CCAS tower. There is some energy savings from the use of a smaller blower in the CFAS tower. However, the resulting reduction in operating cost does not appear to be high enough to offset (over a reasonable period of time) the additional capital cost of building a CFAS versus a CCAS tower. Also, because the CFAS tower is operated at a much higher air-to-water ratio, a larger volume of contaminated air is generated, although the contaminant loading (mass of contaminant per unit time) in the air from both towers is the same for the same stripping efficiency. If contaminant levels in the airstream are such that the air can be discharged directly to the ambient, then the larger air volume is not a concern. However, if the airstream requires treatment by catalytic oxidation, then operating costs are higher for the CFAS tower because a larger airstream has to be heated to the catalyst operating temperature.

Commercially available catalysts, such as the ones used in this study, are suitable for use in air stripping operations for treatment of the high-humidity airstream from the towers. The innovative photocatalytic technology is a promising development with potential for high destruction efficiencies and reduction in operating costs.

## H. RECOMMENDATIONS

In general, a combination of air stripping and catalytic oxidation was found to be a good method for remediation of organics in groundwater. The crossflow air stripping concept did not appear to offer any significant cost advantages over conventional air stripping, for the range of test conditions studied. There may be other advantages, however, such as reduced fouling potential and stripping of other compounds with low Henry's Law constant, that could be evaluated in the future.

If contaminant levels in the groundwater, and hence, in the airstream are very low, but regulatory or other concerns still require treatment, then carbon adsorption treatment of the airstream may be more economical compared to catalytic oxidation. However, if air stripping followed by carbon adsorption is to be used, then it may be easier to treat the water itself directly with carbon. Previous research efforts by the Air Force have found air stripping to be much more cost effective compared to carbon treatment of the water. The relative attractiveness of the two approaches should be evaluated on a site-specific (and contaminant-specific) basis.

Further research in air stripping should include evaluation of the CFAS tower with compounds having low Henry's Law constants other than DCA (e.g., chloroform, methyl ethyl ketone, etc.) to observe any advantages over the CCAS tower. The CFAS tower should be tested at higher air-to-

water ratios and higher liquid loading than were achieved in this study. This will enable the estimation of mass transfer coefficients over a wider range of air and water loadings and over a range of contaminants (with different Henry's Law constants). If possible, air-to-water ratios should be taken high enough to estimate the onset of flooding in the CFAS tower. Also, it would be desirable to study the performance of the CCAS and CFAS towers over longer periods of time to observe how the effects of microbial fouling and iron precipitation vary between the two towers.

Future research should further evaluate the potential for formation of any by-products and products of incomplete combustion in the treated airstream from the catalysts. In this study, a detailed analysis of the airstreams from the bench-scale conventional catalysts was performed, and no significant by-products of concern were detected. However, the low initial concentrations of VOCs in the groundwater (and therefore in the feed air to the catalysts) made detection difficult. The catalysts should be tested at higher concentrations of VOCs to confirm these results.

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## ABBREVIATIONS AND ACRONYMS

AFB	Air Force Base
AIR	Adsorption-Integrated-Reaction process
AS	Allied Signal, Inc.
CCAS	countercurrent air stripping
CFAS	crossflow air stripping
cfm	cubic foot (feet) per minute
DCA	1,2-dichloroethane
DCE	1,2-dichloroethylene
DW	downstream
FB	field blank
FID	flame-ionization detector
GC	gas chromatograph
gpd	gallon(s) per day
gpm	gallon(s) per minute
HP	Hewlett Packard
HT	Haldor Topsoe A/S
ID	inside diameter
MEK	methyl ethyl ketone
PCE	perchloroethylene
ppb	part(s) per billion
ppbv	part(s) per billion by volume
ppm	part(s) per million
ppmv	part(s) per million by volume
scfm	standard cubic foot (feet) per minute
SE	Salem Engelhard, Inc.
TCE	trichloroethylene
UA	University of Akron
UV	ultraviolet
UW	upstream
VC	vinyl chloride
VOA	volatile organic analysis
VOC	volatile organic carbons

## SECTION I INTRODUCTION

### A. OBJECTIVE

The goal of this project was to field-demonstrate *crossflow air stripping* and *catalytic oxidation* as cost-effective treatment technologies for cleanup of contaminated groundwater. The field demonstration was performed at Dover Air Force Base (AFB) in Dover, Delaware. Specific objectives of this demonstration were (1) to compare the volatile organic compound (VOC) removal efficiency of the crossflow air stripper to that of a conventional countercurrent air stripper, and (2) to evaluate the performance of several types of commercial catalysts in destroying halogenated hydrocarbons in the off-gas from the air strippers. The overall goal was to provide a credible database to be used by the U.S. Air Force in selecting the best available air-stripping and emissions control technologies for the cleanup of contaminated groundwater.

### B. BACKGROUND

In many areas at Dover AFB, spills, leaks, and seepage from disposal sites have resulted in contamination of groundwater with VOCs, including chlorinated compounds. Remediation measures include in situ measures, in which the effectiveness is extremely sensitive to site conditions, and ex situ measures, which involve pumping the groundwater to the surface for treatment and returning the treated water to the aquifer or discharging it to a body of surface water. The contaminants removed from the water are disposed of in a manner that considers their nature, quantity, cost of disposal, and environmental impact.

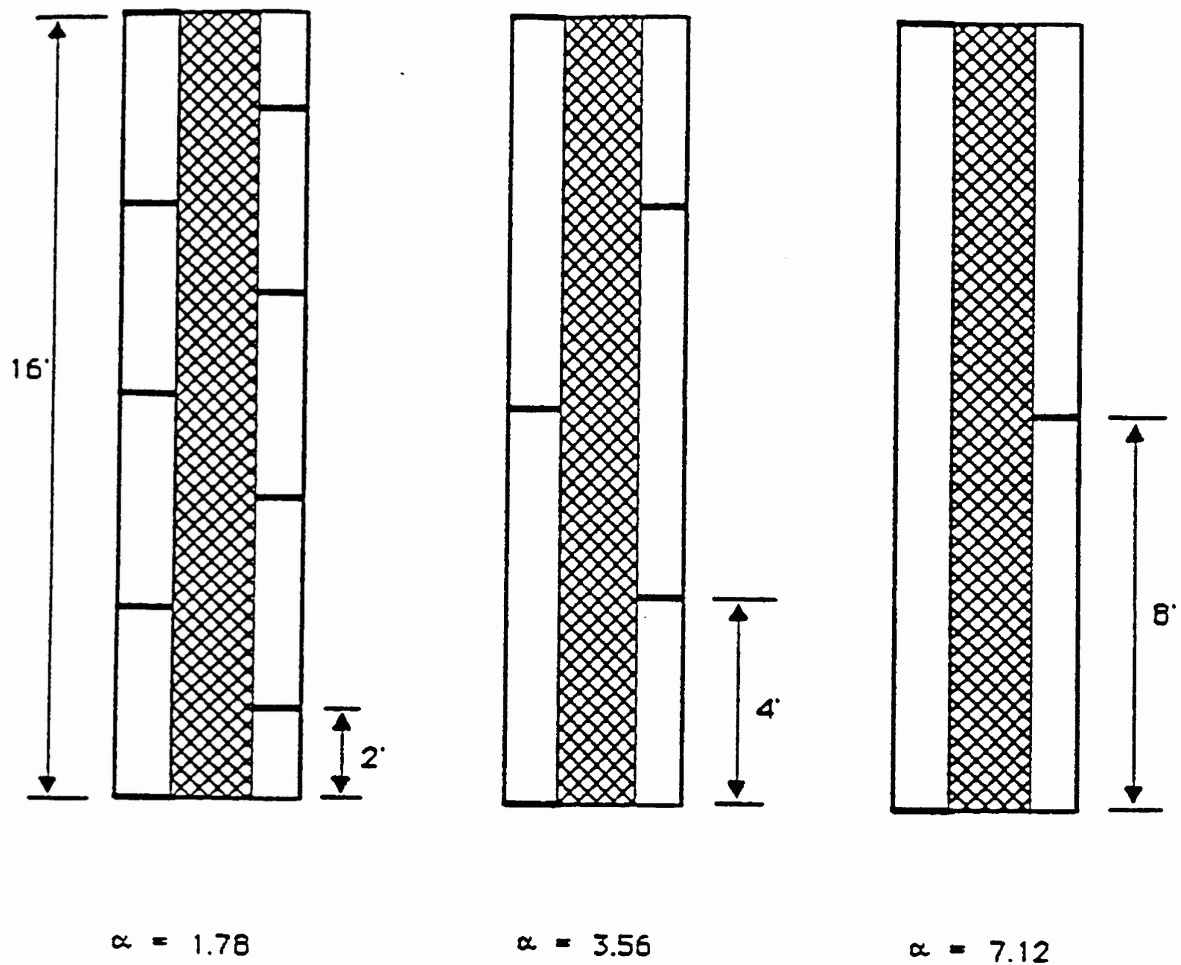
#### 1. Process Background

Air stripping is becoming the preferred process for removing VOCs from groundwater. It is generally less costly than the other available methods such as adsorption, oxidation, and steam stripping. Air stripping towers typically are designed in a counterflow arrangement. The crossflow air stripping concept was first introduced by Baker and Shyrock (1961) and was developed by researchers at Louisiana State University (Thibodeaux, 1969; Wood et al., 1990; Mertoetomo et al., 1993; Verma et al., 1994). In the crossflow arrangement, a number of partial baffles are spaced evenly throughout the tower, and the packing is placed in the center of the tower between the baffles.

Figure 1 displays three of the baffle configurations used in this study. The overall operation is still countercurrent. Water enters at the top of the tower and air enters at the bottom. The difference is that the airstream is deflected by the *baffles*, causing it to pass through the packing at approximately 90 degrees. This process reduces the gas velocity and, therefore, *reduces the pressure drop* across the tower. Under potentially liquid diffusion-controlled conditions, the removal efficiency and mass transfer coefficient are independent of the air velocity. The crossflow design takes advantage of this fact by accommodating a larger exchange of air at lower air velocities and claims to provide similar removal efficiencies at lower pressure losses.

Two series of tests were conducted during this study:

- First, a *preliminary test* was conducted during the fall of 1993 to evaluate a range of operating conditions for the air stripping and catalytic oxidation components.



$$\alpha = \frac{\text{cross-sectional area for air flow}}{\text{cross-sectional area for water flow}}$$

cross-sectional area for water flow = 1.885 sq. ft.

**Figure 1. CFAS Baffle Configurations.**

- Second, an *extended test* was conducted during the spring of 1994. In this test, the stripping towers and catalytic units were operated continuously at steady-state conditions for 10 weeks.

## 2. Site Background

The crossflow air-stripping and catalytic oxidation system at Dover AFB was located in the areas where concentrations of 1,2-dichloroethane (DCA), 1,2-dichloroethylene (DCE), trichloroethylene (TCE), perchloroethylene (PCE), and vinyl chloride (VC) historically have been detected in the groundwater. Of these compounds, DCA is of particular interest because it has a relatively *low Henry's law constant*, making it more difficult to remove by air stripping.

## 3. Extraction Wells

Three pumping wells (designated Well 1, Well 2, and Well 3) were installed in May 1993 to provide groundwater to the air-stripping process. They were designed so that a total discharge of 100 gallons per minute (gpm) could be achieved for approximately 6 months.

## 4. Contaminant Levels

Groundwater samples were collected at various times from the monitoring and extraction wells on the site. Tables 1 and 2 present the results of the organic and inorganic analyses. The

**TABLE 1. GROUNDWATER SAMPLE ANALYSIS RESULTS FOR ORGANIC COMPONENTS**

Date	Well	Concentration $\mu\text{g/L}$				
		<i>trans</i> -DCE	<i>cis</i> -DCE	DCA	TCE	PCE
1990 <sup>(a)</sup>	MW-39S	62 <sup>(b)</sup>	—	69	150	93
1990 <sup>(a)</sup>	MW-206M	16 <sup>(b)</sup>	—	110	100	40
1990 <sup>(a)</sup>	M2-04-11	140 <sup>(b)</sup>	7	—	630	4,500
5/93 <sup>(b)</sup>	Well 1 <sup>(d)</sup>	< 1	1	7	6	5
5/93 <sup>(b)</sup>	Well 2 <sup>(d)</sup>	< 1	1	82	77	47
5/93 <sup>(b)</sup>	Well 2 <sup>(e)</sup>	< 1	10	110	67	40
5/93 <sup>(b)</sup>	Well 3 <sup>(d)</sup>	< 1	5	21	26	23
9/93 <sup>(c)</sup>	Combined <sup>(d)</sup>	< 1	13	70	74	51
11/93 <sup>(c)</sup>	Combined <sup>(e)</sup>	< 1	4	41	42	44
11/93 <sup>(c)</sup>	Combined <sup>(e)</sup>	< 1	4	39	39	43

- (a) Groundwater sample analyzed from upstream and downstream monitoring wells (historical data from site RI/FS report).
- (b) Samples withdrawn from extraction wells to be used for groundwater supply.
- (c) Samples taken from the combined flow from Extraction Wells 1, 2, and 3.
- (d) Analysis performed using purge and trap and FID field methods.
- (e) Analysis performed using purge and trap and EPA Method 624 in an offsite laboratory.
- (f) Combination of both *cis*- and *trans*- isomers.

**TABLE 2. GROUNDWATER SAMPLE ANALYSIS RESULTS  
FOR INORGANIC COMPOUNDS**

Date	Well	Total Metal Concentration $\mu\text{g/L}$					
		Calcium	Chromium	Hexavalent Chromium	Iron	Magnesium	Mercury
2/93 <sup>(a)</sup>	DW-1 <sup>(e)</sup>	6,300	14.5	5.5	7,045	2,960	<0.2
2/93 <sup>(a)</sup>	UW-1	6,950	7	<5	11,800	3,190	<0.2
2/93 <sup>(b)</sup>	FB-1	2,160	<5	<5	209	600	<0.2
5/93 <sup>(c)</sup>	Well 1 <sup>(e)</sup>	2,210	11	NA	610	1,125	0.45
5/93 <sup>(c)</sup>	Well 2	2,370	<10	NA	730	1,240	<0.2
5/93 <sup>(c)</sup>	Well 3	3,040	<10	NA	790	1,490	<0.2
9/93 <sup>(c)</sup>	Well 1	NA	NA	NA	NA	NA	<0.2
11/93 <sup>(d)</sup>	Combined <sup>(e)</sup>	2,745	<10	NA	370	1,375	<0.2
11/93 <sup>(d)</sup>	Combined	2,780	<10	NA	320	1,430	<0.2

(a) Samples were analyzed from upstream (UW) and downstream (DW) monitoring wells.

(b) Field blank (FB).

(c) Samples withdrawn from the extraction wells (Wells 1, 2, and 3) to be used for groundwater supply for testing.

(d) Samples taken from the combined flow from Extraction Wells 1, 2, and 3.

(e) Results are an average of two measurements.

samples from 1990 indicate relatively high concentrations of DCE, DCA, TCE, and PCE. In May 1993, extraction wells (Wells 1, 2, and 3) were installed and groundwater samples were collected. These samples had concentration levels much *lower* than the values obtained in 1990. The decrease probably is due to contaminant dispersion over time and screening of the extraction wells at a larger interval than screening of the monitoring wells. Samples of the combined water from the three extraction wells were analyzed periodically from September to November 1993. Resulting halogenated hydrocarbon concentrations were similar to those obtained in May 1993. A relatively high level (approximately 12 ppm) of *iron* was discovered in an upstream monitoring well in February 1993, and it was decided that pretreatment of the groundwater with a chelating agent would be advisable to prevent any iron from precipitating out in the air-stripping towers during the preliminary test. *Sodium citrate* was used as a chelating agent and was added to the groundwater at a level of 55 ppm, based on a 1:1 molar ratio with the maximum iron concentration observed in the February 1993 groundwater sample. However, because the citrate was found to cause microbial growth fouling in the towers, and because iron levels in the water dropped as testing progressed, pretreatment of the groundwater with citrate was *eliminated during the extended test*.

Also, the fact that VOC concentrations dropped to very low levels after the extraction wells were allowed to stabilize posed a challenge in terms of obtaining meaningful data. Therefore, it was decided that the key contaminant of interest, DCA, would be *spiked* into the inlet water to the stripping towers at a level of 1 ppm. Thus, the concentration of the feed water was maintained at approximately 1 ppm throughout the preliminary and extended test periods. The 1-ppm level was selected on the basis of the amount of DCA that the research team felt would be acceptable in the effluent water under existing permits. The effluent water from the towers was released to a surface water body. Analytical detection limit considerations in the effluent water also were a determinant in setting the spike level.

## SECTION II PILOT DESIGN SUMMARY

### A. PILOT PLANT DESCRIPTION

The air-stripping and catalytic oxidation system consists of four major components: (1) *extraction and pretreatment* of groundwater, (2) *air stripping* of VOCs, (3) *catalytic destruction* of VOCs, and (4) *hot water tower cleaning* system. Components (1), (2), and (4) are shown on the left, top, and bottom of Figure 2, respectively. Component (3) is shown on Figure 3. The pilot plant was constructed on a trailer for easy transport to different sites.

Groundwater was extracted from Wells 1, 2, and 3 to obtain a maximum total flow of approximately 100 gpm. The water was pretreated with *sodium citrate* to prevent scaling and rust deposition on the packing in the air stripping towers. The pretreatment tank also was used to spike the water with *DCA* to obtain an approximate inlet concentration, at the towers, of 1,000 ppb (1 ppm). *Spiking* was necessary because the unexpectedly low concentrations of *DCA* in the groundwater were insufficient to test the range of conditions needed to demonstrate the new technology. A 1,000-ppb inlet concentration was needed so that the concentration of *DCA* in the outlet stream would be in a detectable range and the variation in stripping efficiency with variation in factors such as air-to-water ratio could be observed.

The crossflow air-stripping (CFAS) tower and the conventional countercurrent air-stripping (CCAS) tower were operated side by side in a *parallel* configuration. Water leaving the towers was collected in the surge tank at the base of the towers and discharged to a drainage ditch.

The *airstreams* leaving the two towers were *combined* and directed to the following downstream VOC destruction units:

- During the *preliminary test*, the bulk of the air leaving the stripping towers was directed to a 500-standard cubic foot per minute (scfm) *fluidized-bed* catalytic oxidizer manufactured by ARI International, Inc. During the *extended test*, the bulk of the air was directed to a 50-scfm *fixed-bed photocatalytic* oxidizer manufactured by KSE, Inc. The photocatalytic unit is an innovative technology that uses a combination of ultraviolet (UV) light and a proprietary catalyst.
- A small portion (< 1 scfm) of the air leaving the stripping towers was directed to *four bench-scale fixed-bed* catalytic oxidation units with commercially available catalysts. The four catalysts tested during the preliminary test were provided by:
  - University of Akron (UA), Akron, Ohio
  - Haldor Topsoe A/S (HT), Lyngby, Denmark [Catalyst code: CK-306]
  - Allied Signal, Inc. (AS), Tulsa, Oklahoma [Catalyst code: PZM-5063IND]
  - Salem Engelhard, Inc. (SE), South Lyon, Michigan [Catalyst code: VOCAT 350 HC].



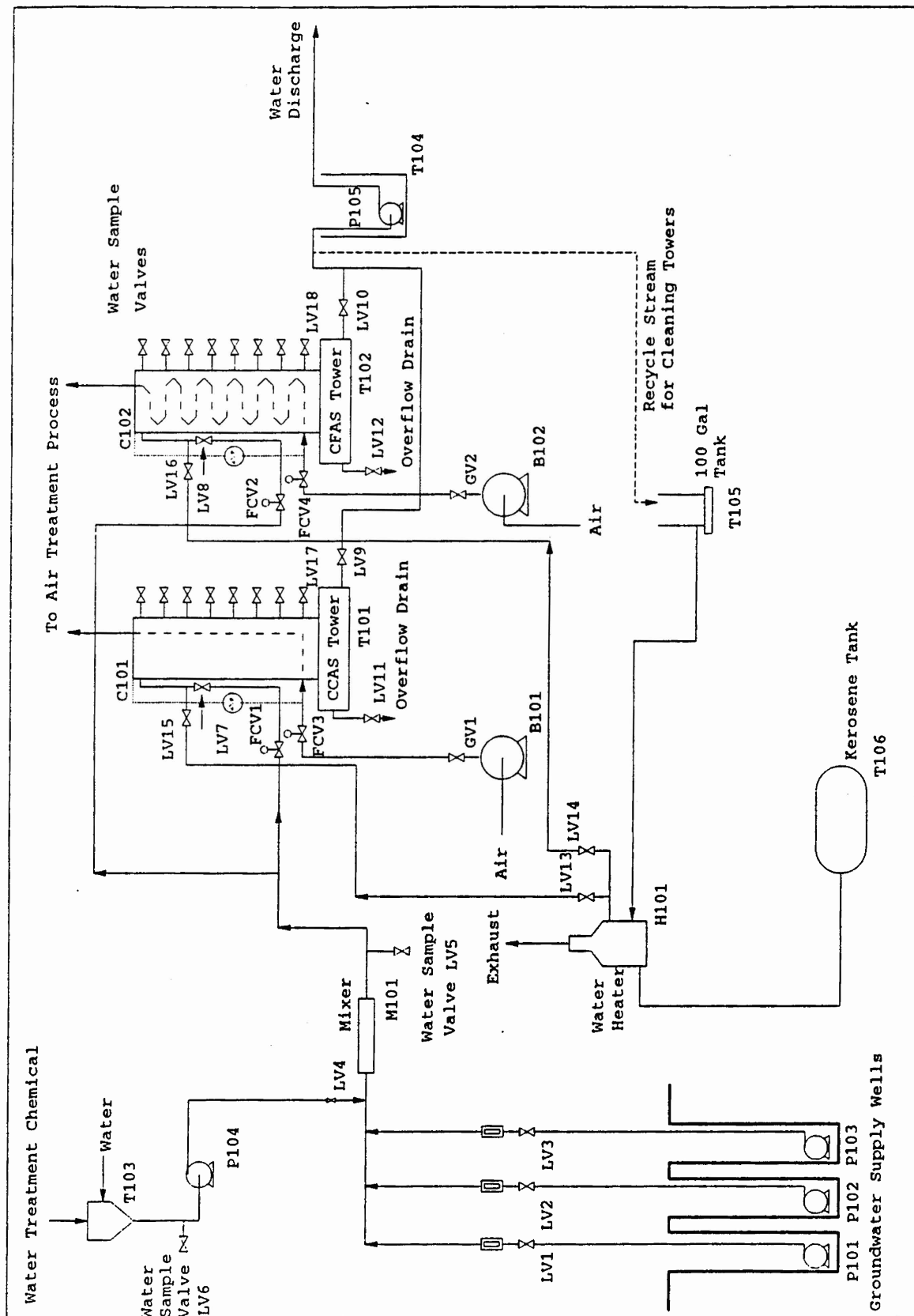


Figure 2. Air Stripping Process Flowsheet.

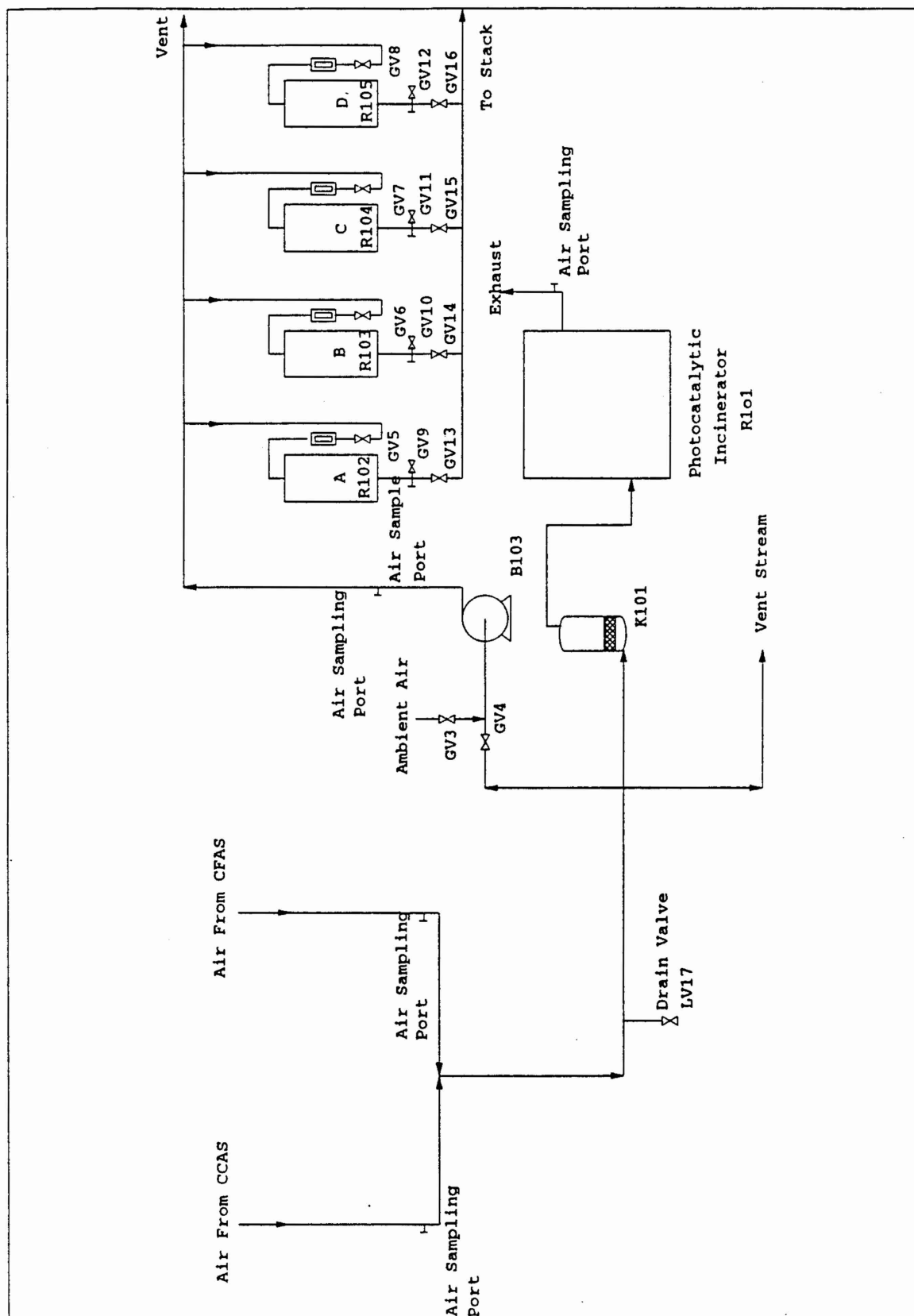


Figure 3. Air Treatment System.

During the *extended test*, the HT catalyst was replaced with an *experimental new catalyst*, designated in this report as Catalyst X. The replacement was not determined by the HT catalyst performance, but was done to expand the Air Force's information database.

The fluidized-bed unit was heated with a propane burner. The fixed-bed units were heated with an electric heater. The VOC destruction units were operated concurrently, and airstreams leaving them were combined and vented through a common stack.

### 1. Tower Design

Both stripping towers were packed to a 17-foot vertical packing depth. Based on the design parameters for a CCAS tower, 16 to 17 feet of tower packing would remove 99 percent of DCA using an air-to-water ratio of 100. The packing used was 1-inch polyethylene Pall rings. Each tower contained the *same volume* of packing. The inner diameters of the towers were 1.5 feet (CCAS) and 2 feet (CFAS).

Both towers were constructed of aluminum. Two cylindrical sections (8.3 and 8.5 feet high) were used to contain the packing in the CCAS tower. The packing in the CFAS tower was contained using six 2-foot-long sections and two 2.4-foot-long sections, all with flanged ends. Baffles were made of thin aluminum sheets of size similar to the flanged ends. Figure 4 shows the CFAS tower details. The packed portion of each tower was installed on a 2.9-foot-long base piece mounted to the trailer. A 1.5-foot distributor section was placed on the top of each tower to complete the construction. All connections were made using flanges. Both towers were 22.1 feet high.

### 2. Catalytic Oxidation Unit Design

Four bench-scale oxidation units were built for operation with either monolithic or bead catalysts. Each unit was composed of a small fixed-bed chamber, as shown in Figure 5. The chamber was approximately 1.0 inch in diameter and 9 inches in depth. The UA, HT, and AS catalysts were loaded into separate chambers to a bed height of 4 inches. A fourth chamber was filled with the SE catalyst to a bed height of 3 inches. The bed was suspended in the center of a 2,800-watt electrically heated vertical split-tube furnace. A preheater was placed upstream of the furnace to preheat the air before entering the furnace. The bench-scale oxidizers were designed for flow rates of less than 1 scfm.

## B. EXPERIMENTAL DESIGN FOR PRELIMINARY TEST

Tests were conducted to investigate both the stripping efficiency of the towers and the VOC destruction efficiency of the catalytic units. Each stripping test took about 4 to 6 hours. After each operating condition change, the towers were operated at least 30 minutes to reach steady-state before measurements were taken. The parameters investigated included air-stripping tower *design* (CCAS or CFAS tower), *air flow rate*, *water flow rate*, and *baffle spacing*. For the CFAS tower, the baffle spacing was quantified by the dimensionless parameter  $\alpha$ , defined as the ratio of gas flow area to water flow area. The gas flow area is the *vertical* cross-sectional area between two baffles. The water flow area is the *horizontal* cross-sectional packed area. Side-by-side tests of the two towers enabled direct comparison between the CCAS and CFAS towers.

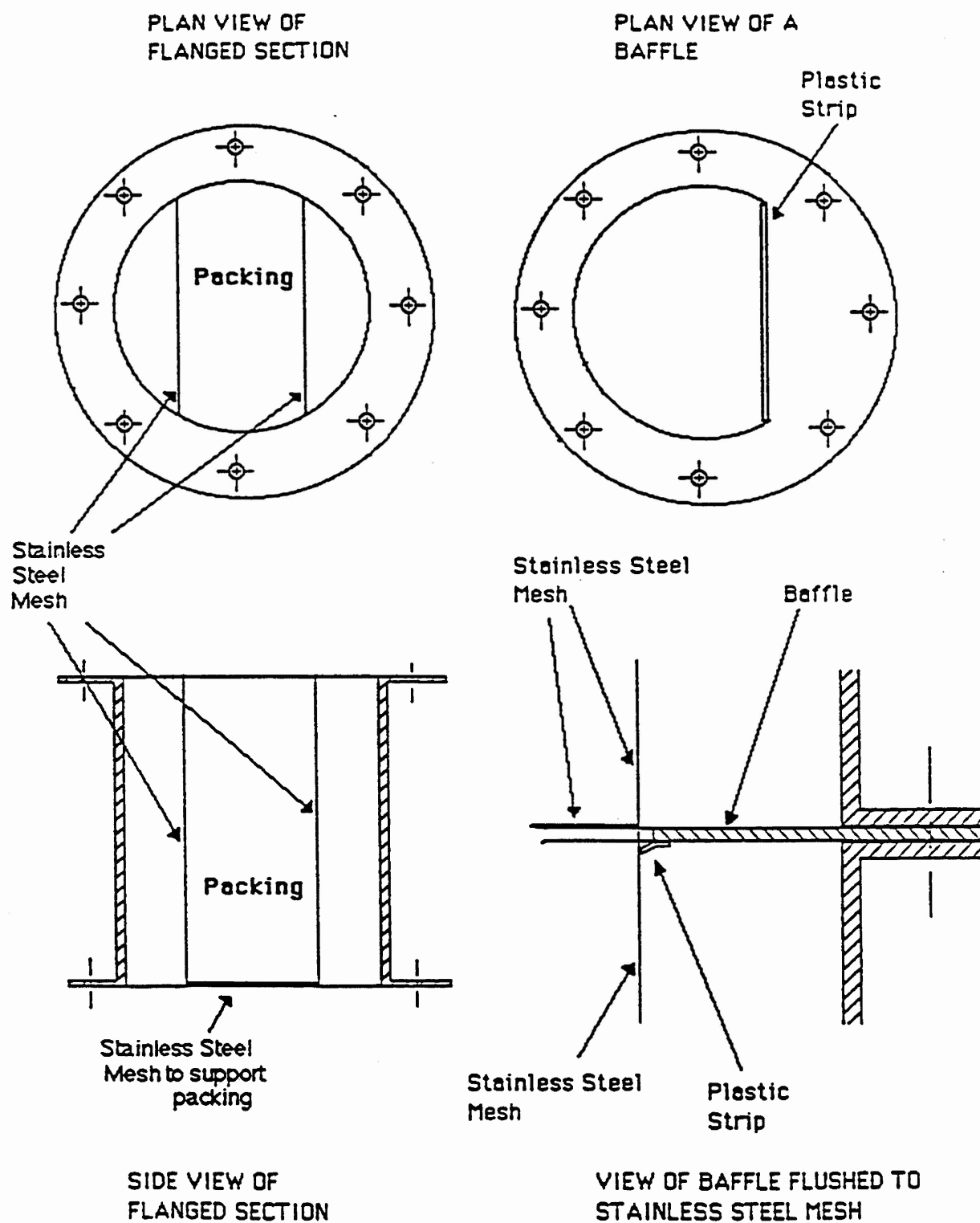


Figure 4. Crossflow Air-Stripping (CFAS) Tower Details.

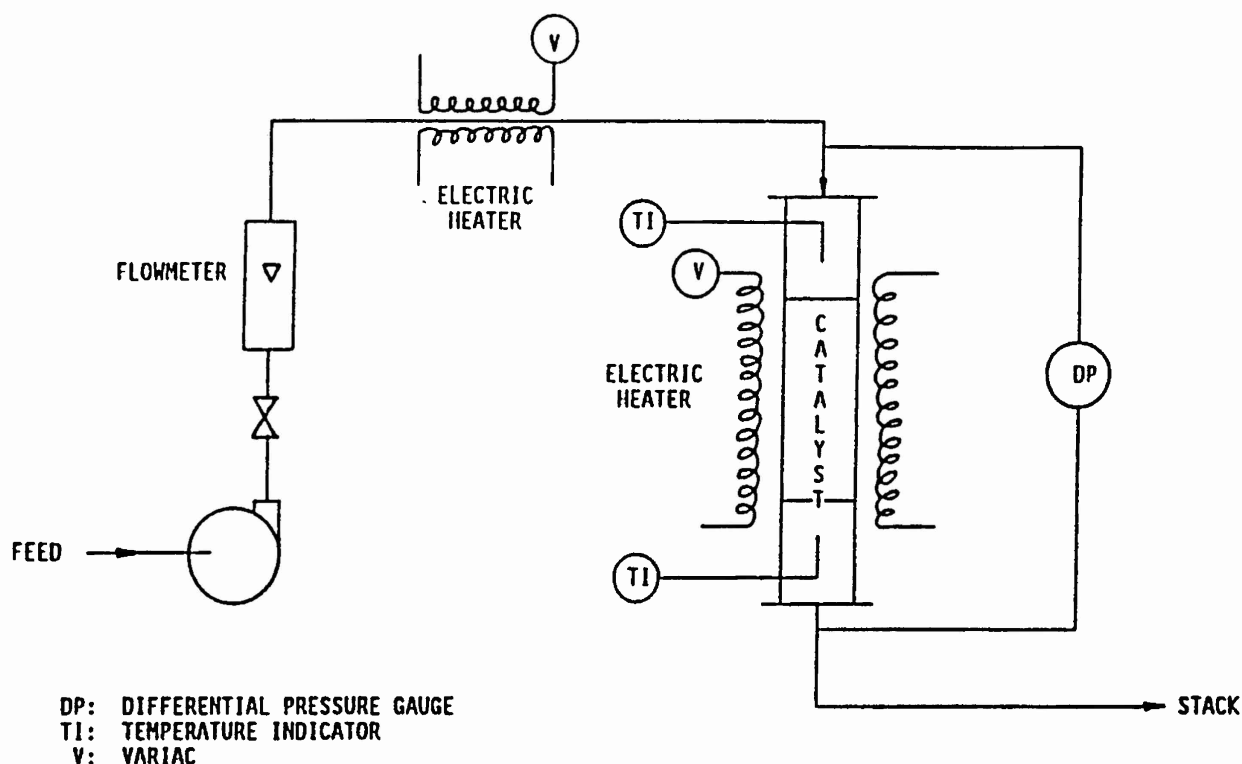


Figure 5. Schematic Diagram of Fixed-Bed Catalytic Oxidizers.

A factorial experiment was used to explore three levels of water flow, three levels of air flow, and three baffle configurations (27 tests) simultaneously with the CCAS and CFAS towers, as follows:

- 20, 35, and 50 gallons per minute (gpm) water flow rate
- 100, 175, and 250 scfm air flow rate
- $\alpha = 7.12, 3.56, \text{ and } 1.78$  (3, 5, and 9 baffles, respectively).

The preliminary test was meant to start with the series of runs with  $\alpha = 1.78$ , but it was discovered later that only 7 baffles were present in this series (designated  $\alpha = D$ ). The topmost and bottommost baffles had been inadvertently left out. This series of runs was, therefore, treated as an extra series designated as  $\alpha = D$ . A total of 36 runs were conducted, plus some additional runs to verify specific field situations.

Each catalyst test took about 4 to 6 hours, depending on the air sampling analysis time. The catalytic units were operated for at least 1 hour at their predetermined temperature before sample collection. The parameters investigated included *space velocity* (the flow of air divided by the length of the catalyst bed) and *temperature*.

### C. STRIPPING TOWER FLOW CHARACTERISTICS

Before the preliminary test started, the flow characteristics of the two towers were evaluated by passing relatively clean water (from the city water supply) through the towers at varying rates. Air

flow rates through the towers also were varied. The *Sherwood-Eckert* plots for the CCAS and CFAS towers are shown in Figures 6 and 7. A modified version of these plots as suggested by the packing manufacturer (Norton Chemical Process Products, Inc.) was used. The modified Sherwood-Eckert plot helps predict the pressure drop in a packed tower. The x-coordinate (X) and the y-coordinate (Y) are defined as follows:

$$X = \frac{L (\rho_g)^{0.5}}{G (\rho_L)^{0.5}} \quad \text{and} \quad Y = \frac{F \cdot G^2 \cdot \nu^{0.1}}{\rho_g (\rho_L - \rho_g)} \quad (1)$$

where

- G = gas flow rate (lb/ft<sup>2</sup>-sec)
- L = liquid flow rate (lb/ft<sup>2</sup>-sec)
- $\rho_L$  = liquid density (lb/ft<sup>3</sup>)
- $\rho_g$  = gas density (lb/ft<sup>3</sup>)
- $\nu$  = liquid viscosity (centistokes)
- F = packing factor (55 for 1-inch Pall rings).

All points corresponding to the 36 test conditions fall below the flooding line for the CCAS tower. The flooding line generally coincides with the line for 2 inches/foot pressure drop for conventional packed towers. For the CFAS tower, the flooding line position is not obvious but is expected to be much higher.

The pressure drops predicted by the packing manufacturer are marked on the plots, but the pressure drops observed for the CCAS tower in the field under test conditions were higher than predicted, as indicated by the points on the plot (Figure 6). For the CCAS tower, the higher observed (versus predicted) pressure drop can be explained by the fact that the losses in the top distributor plate and the bottom support plate were included in the pressure drop measurements in the field. The observed pressure-drop variation with respect to air mass loading for the two towers is shown in Figures 8 and 9. The pressure drop for the CCAS tower increases with increases in water flow rate, whereas the pressure drop for the CFAS tower is relatively insensitive to water flow rate. The pressure drop rises more sharply with air loading in the CCAS tower than in the CFAS tower. Neither tower could be taken to flooding conditions in the field because of the limitations of the air blowers. Only the fact that none of the test conditions caused flooding could be verified. Figures 8 and 9 also indicate that the pressure drop in the CFAS tower generally is an order of magnitude lower than the pressure drop in the CCAS tower.

# Modified Sherwood-Eckert Plot

Countercurrent Tower

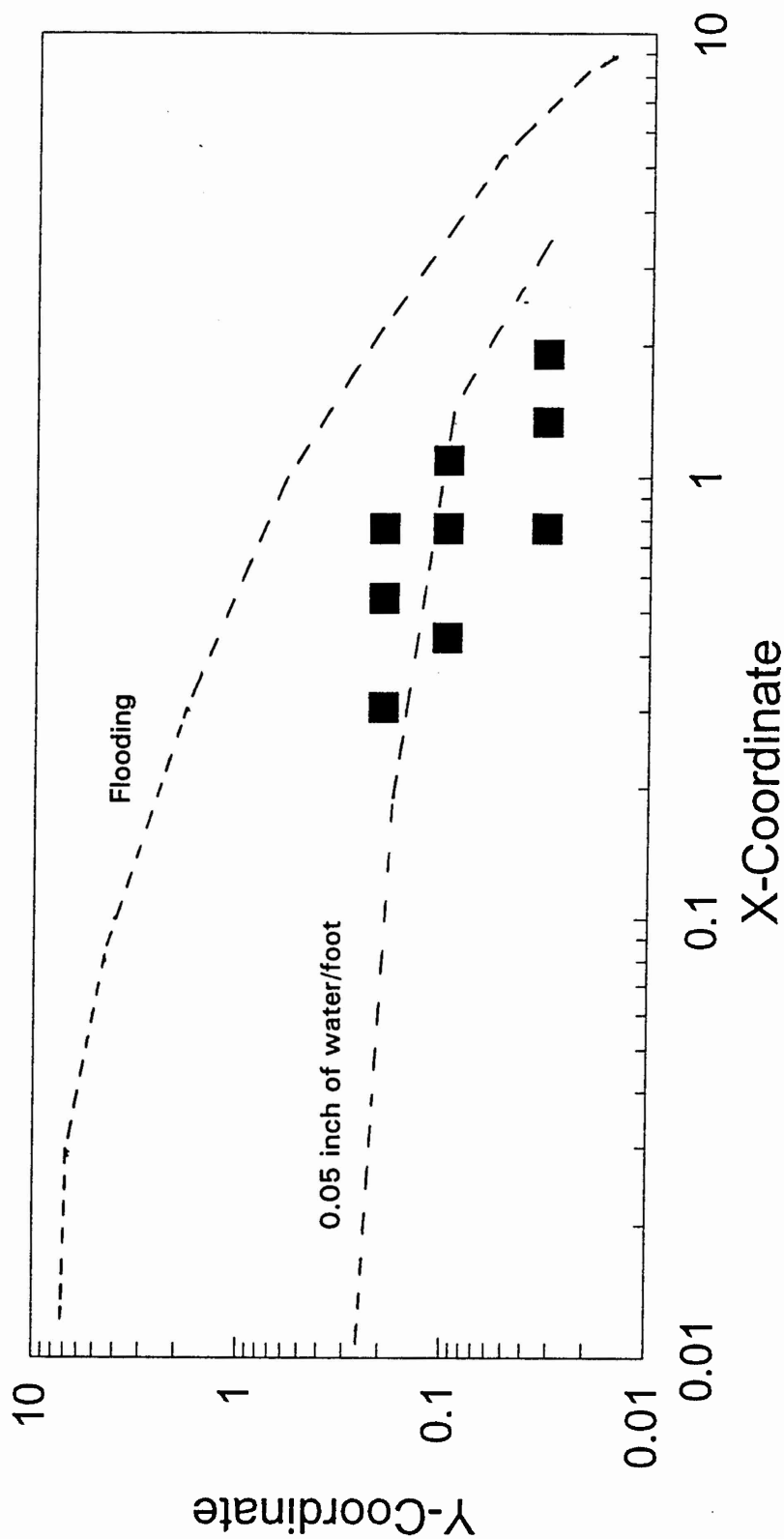


Figure 6. Modified Sherwood-Eckert Plot for the CCAS Tower.

# Modified Sherwood-Eckert Plot

Crossflow Tower

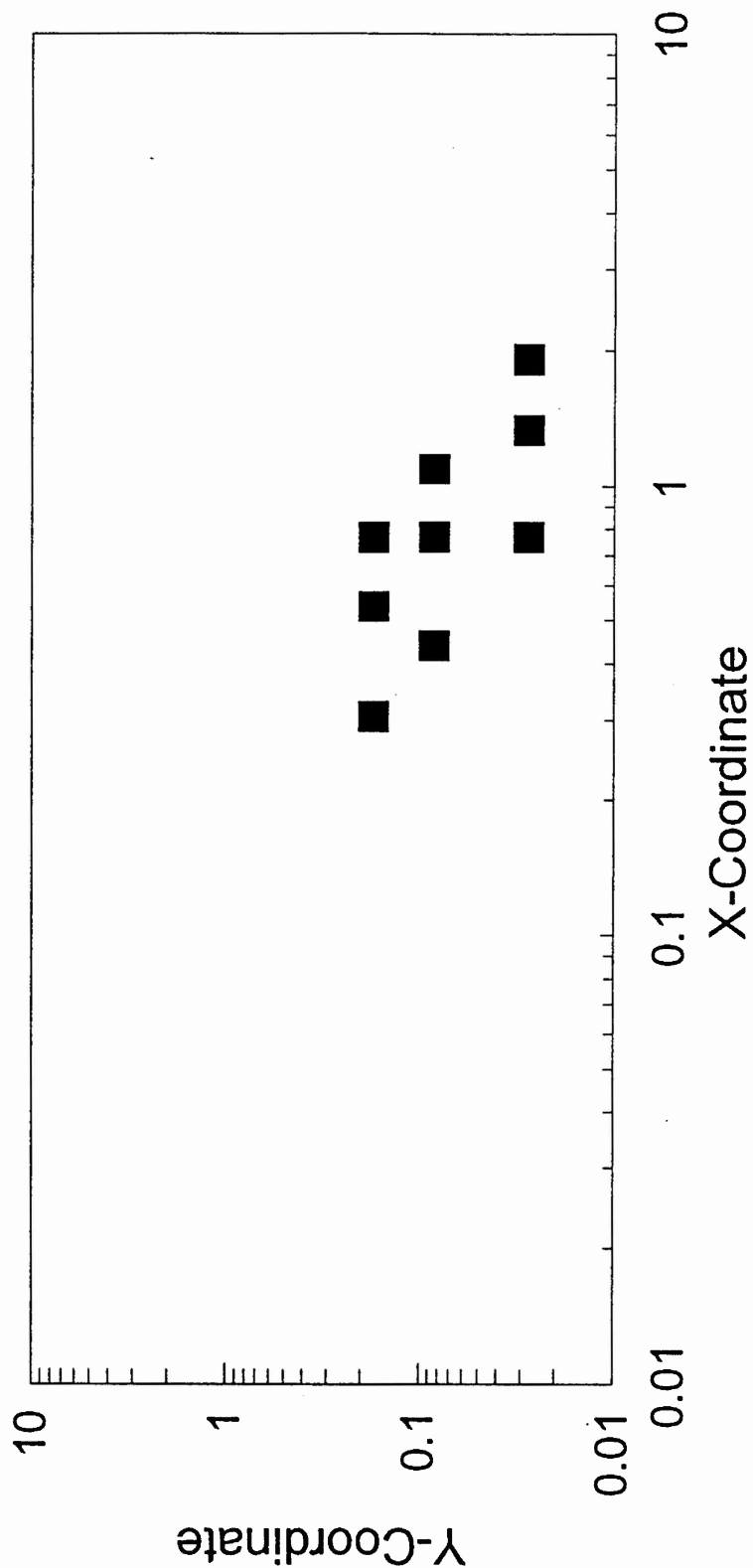


Figure 7. Modified Sherwood-Eckert Plot for the CFAS Tower.



# Pressure-Drop Characteristics

## Countercurrent Tower

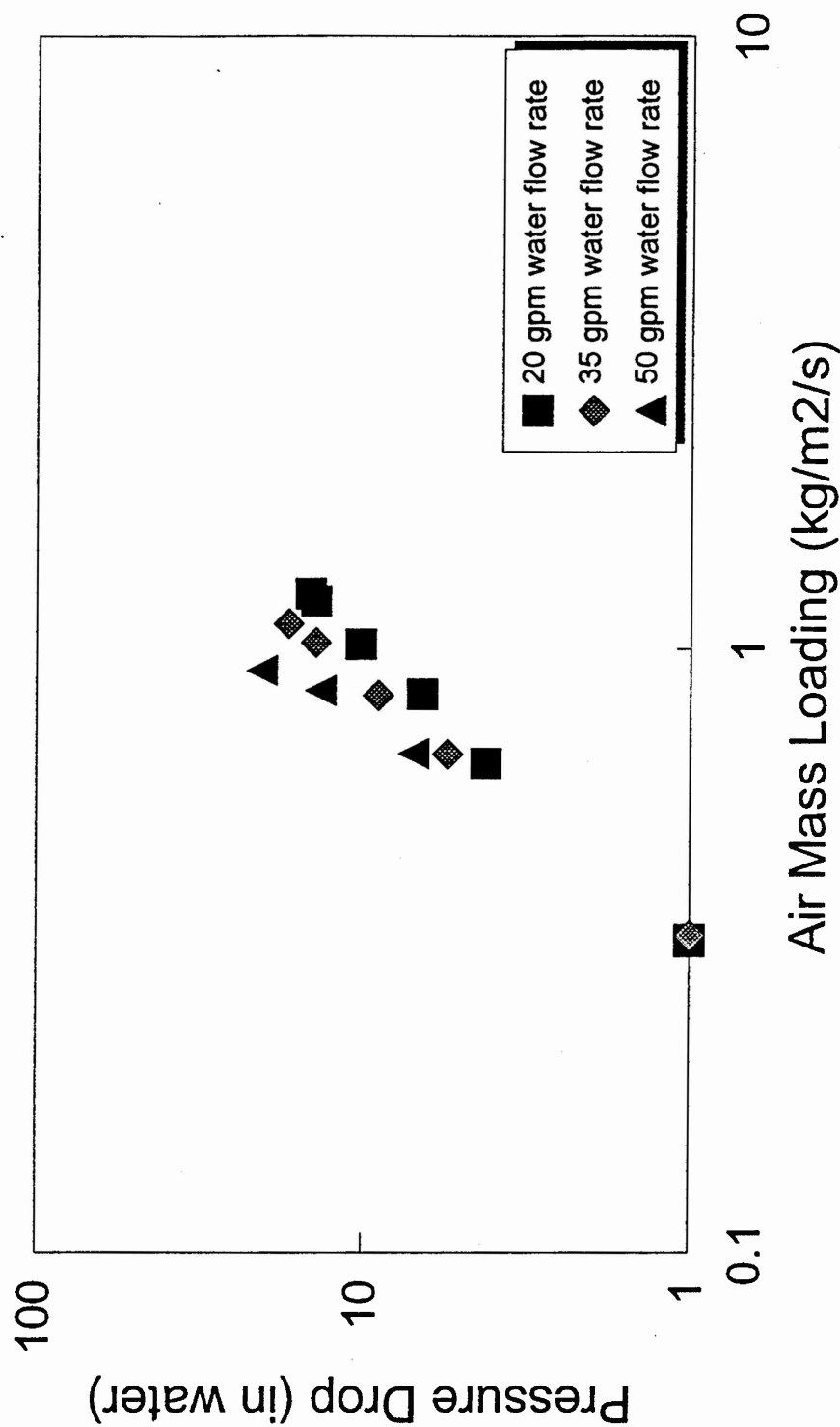


Figure 8. Pressure Drop as a Function of Air and Water Flow Rates for the Countercurrent Tower.

# Pressure-Drop Characteristics

## Crossflow Tower

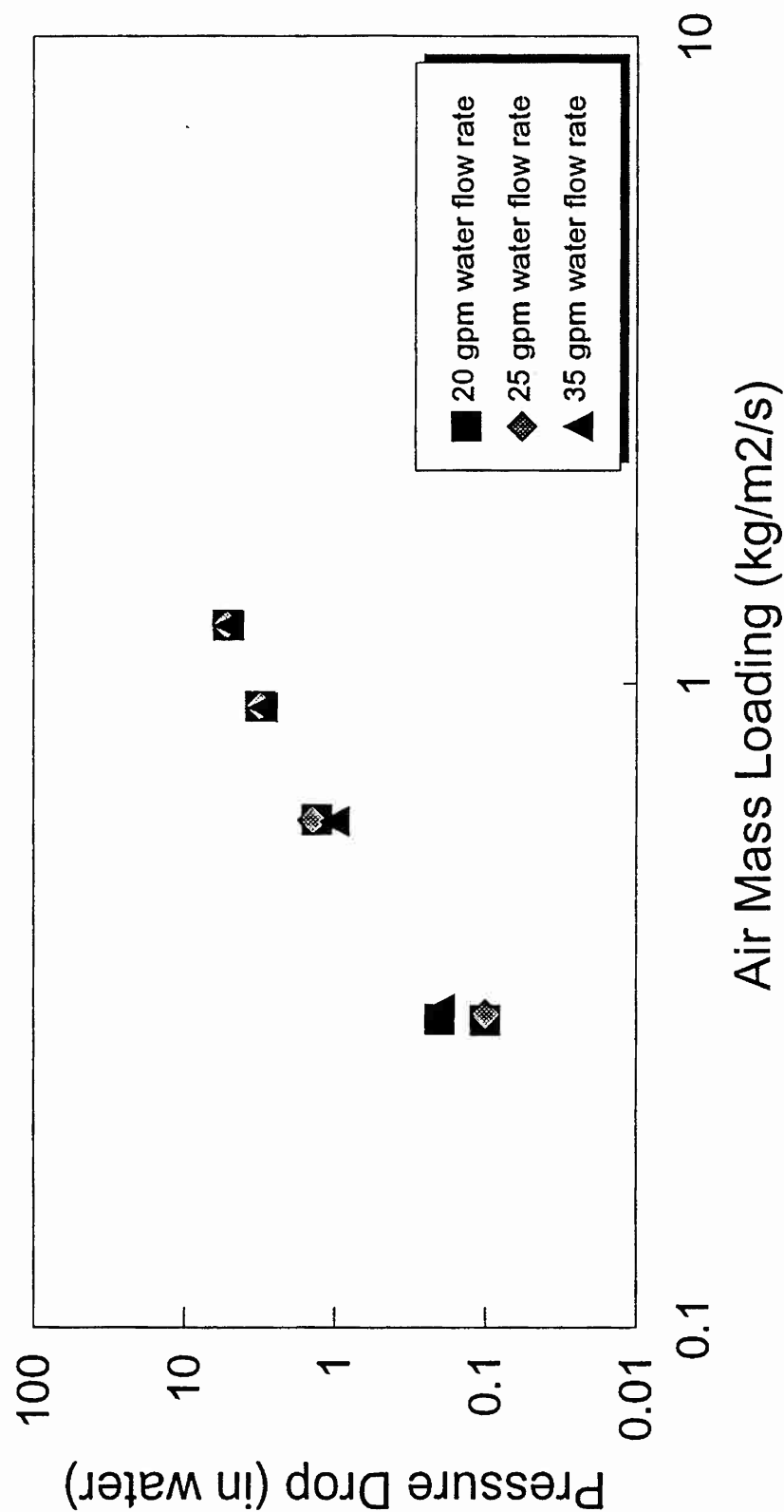


Figure 9. Pressure Drop as a Function of Air and Water Flow Rates for the Crossflow Tower.

### SECTION III ANALYTICAL METHODS

#### A. WATER ANALYSIS

Water analysis was performed using EPA Method 601 as a general guide. The analytical system employed an OI 4460 *purge-and-trap* device equipped with a two-phase sorbent trap (Carbopack® B/Carbosieve® S-III) for collecting the organics purged from the water samples. Analytical separation was performed with a Varian 3700 gas chromatograph (GC) using an HP-1 (Hewlett-Packard) fused silica capillary column (60 meters  $\times$  0.53 millimeter inside diameter [ID]) with a flame-ionization detector (FID). A Nafion™ dryer reduced the moisture loading on the sorbent trap to enhance the stability of the FID.

The system was calibrated for vinyl chloride, *cis*- and *trans*-1,2-DCE, 1,2-DCA, TCE, and PCE. A single-point calibration standard and blank water samples were analyzed daily. Duplicate sample analyses and matrix spike analyses were performed periodically. All calibration standards were prepared prior to field testing. The standards were prepared in a solution of methanol, sealed in glass ampules, and stored in a freezer. Headspace-free water samples were collected in volatile organic analysis (VOA) vials and refrigerated. If samples could not be analyzed within 7 days, a few drops of sulfuric acid were added to prevent biodegradation of the compounds of interest. The detection limit for the compounds of interest was 1 part per billion (ppb) for a 5-milliliter sample.

Typical chromatograms of a spiked inlet (feed) water sample and an outlet water sample (after air stripping) are presented in Figures 10 and 11. Vinyl chloride and *cis*- and *trans*-1,2-DCE

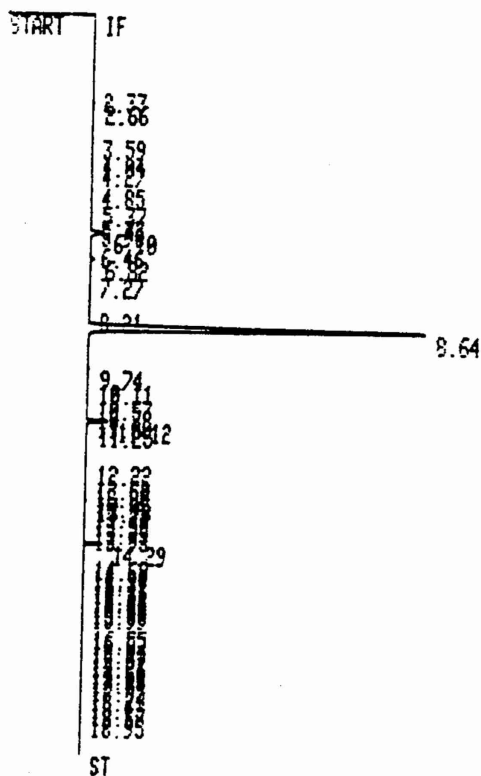


Figure 10. Sample Chromatogram of the Inlet Water to the Towers.

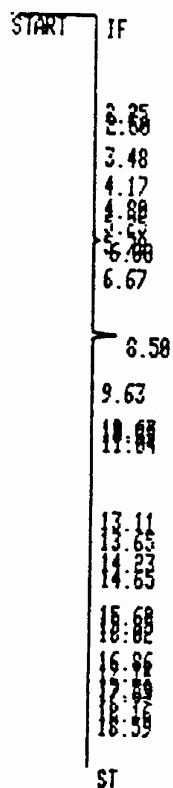


Figure 11. Sample Chromatogram of the Outlet Water from the CFAS Tower.

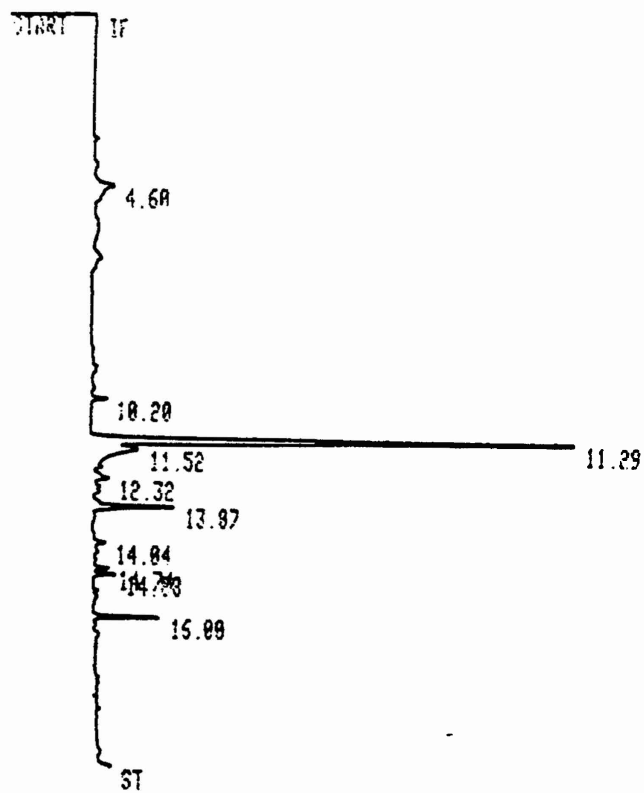
concentrations were too low to be detected by the gas chromatograph. The peak eluting at a retention time of about 8.5 minutes on both chromatograms is DCA. TCE and PCE appear only on the chromatogram of the inlet water sample. They elute at 11.1 and 14.3 minutes, respectively. The concentrations of these compounds in the outlet water are below the sensitivity of the gas chromatograph.

## B. AIR ANALYSIS

The analytical system for the air analysis employed a *two-phase sorbent trap* (Tenax TA/ Carboxen 1000) to collect the organic components in the air sample. A sampling pump with mass flow controller system was installed downstream of the trap so that the sample would be pulled into the trap at a uniform rate. The analytical separations were accomplished with an HP 5890 GC using an HP-1 fused silica capillary column (60 meters  $\times$  0.53 millimeter ID) with an FID.

The system was calibrated for VC, *cis*- and *trans*-1,2-DCE, methyl ethyl ketone (MEK), 1,2-DCA, TCE, and PCE. A single-point calibration and blank air samples for analysis were taken daily. Duplicate sample analyses and matrix spike analyses were performed periodically. The gas calibration standard was made up and stored in a constant-temperature high-pressure cylinder. The volume of calibration gas was sufficient to last for the duration of the testing.

Figure 12 depicts a typical chromatogram of the outlet airstream from the crossflow tower. The VC, *cis*- and *trans*-1,2-DCE, and MEK concentrations were too low to be detected by the gas chromatograph. DCA, TCE, and PCE were seen on all of the outlet airstream chromatograms. The peaks eluted at retention times of 11.3 minutes for DCA; 13.1 minutes for TCE; and 16.0 minutes for PCE.



**Figure 12. Sample Chromatogram of the Combined Air Outlet from the Towers (Inlet to the Catalysts).**

## SECTION IV

### AIR-STRIPPING TOWER TESTING — PRELIMINARY TEST

The preliminary test to evaluate the performance of the air stripping and catalytic oxidation system at different test conditions was conducted from August to November, 1993.

#### A. TEST DESCRIPTION

##### 1. Air-Stripping Test Conditions

The 36 test runs were conducted on the air-stripping towers at the operating conditions indicated in Table 3. Four baffle arrangements were tested for the CFAS tower. The  $\alpha = D$  baffle configuration is similar to  $\alpha = 1.78$ , except that the topmost and bottommost baffles were left out. This would serve to reduce the effective height of the tower. For each baffle arrangement, nine test runs were conducted at different water and air flow rates. A few test runs were repeated to evaluate consistency, and *extra* runs (E1, E2, X1, and X2) were conducted at conditions determined in the field.

##### 2. Process Description

Groundwater was pumped from Wells 1, 2, and 3 and combined in a manifold. Sodium citrate solution was added to the groundwater, which then flowed through a mixing pipe. A *metering pump* controlled the rate of addition to provide a 55-ppm concentration in the groundwater. DCA also was introduced into the inlet water with the citrate solution to increase the inlet water DCA concentration to approximately 1,000 ppb. The sampling port downstream from the mixing pipe allowed collection of inlet water samples just before the water entered the towers.

The water flow rate to each tower was controlled automatically using a vortex *flowmeter* and an electrically operated *diaphragm valve*. The water passed through a *distributor*, located at the top of each tower, to create an even distribution of water. Water was collected from nine sampling ports on the sides of each tower at different packing elevations. The treated water exited at the base of the towers into a *surge tank*. A submersible sump pump inside the tank (level-controlled) periodically pumped the water into a drainage ditch.

Air was supplied directly to the base of each tower using two blowers of ~250 scfm capacity each. The air flow rate was controlled automatically using a vortex *flowmeter* and an electrically operated *butterfly valve*. The airstreams leaving the towers were combined and directed to the VOC catalytic destruction units located downstream of the stripping process. Air samples were collected using a gastight syringe from a sampling port placed in the exit lines of each tower.

##### 3. Operation and Sampling

Operations were initiated by turning on the two *main blowers* for the towers and the three well pumps. The smaller *booster blower* for the catalytic incinerators, the discharge pump, and the metering pump also were turned on at this time from the control panel inside the trailer. The well pumps were operated at least 1 hour before testing to obtain a consistent concentration of VOCs in the groundwater. During the day, after changing test conditions, the towers were operated at least 30 minutes before new testing was initiated. After reaching *steady-state*, operating conditions were

**TABLE 3. AIR-STRIPPING OPERATING CONDITIONS AND TEST RESULTS**

Day	Test ID	Alpha	Flowrates Through Towers		Pressure Drop (inches water)		Volumetric Air/Water Ratio	% Removal	
			Water (gpm)	Air (scfm)	CCAS	CFAS		CCAS	CFAS
1	2	D*	20	100	1.0	0.2	37	85.3	67.7
6	4	D	35	100	1.0	0.1	21	60.3	57.0
6	3	D	35	250	7.5	0.2	53	89.8	82.2
7	6	D	20	175	2.7	0.1	65	97.3	91.8
8	2	D	20	100	1.0	0.1	37	88.2	77.5
8	2	D	20	100	1.0	0.1	37	86.9	72.9
13	8	D	35	175	3.5	0.1	37	86.5	74.3
14	5	D	50	250	17.5	0.7	37	80.0	64.5
14	1	D	50	175	6.0	0.2	26	65.6	52.4
15	9	D	50	100	2.0	0.2	15	48.1	33.3
18	7	D	20	250	11.0	7.0	94	98.1	89.3
42	E1	D	20	295	6.0	0.3	110	99.2	93.0
42	E2	D	20	295	8.0	0.3	110	98.7	92.7
43	7	D	20	250	11.5	5.2	94	98.9	—
43	6	D	20	175	8.0	4.6	65	98.0	88.5
48	18	3.56	50	100	2.5	0.2	15	49.7	35.4
49	17	3.56	35	175	5.0	0.3	37	86.7	69.5
49	12	3.56	35	250	9.0	0.6	53	94.4	79.3
49	13	3.56	35	100	1.5	0.1	21	64.1	52.6
50	11	3.56	20	100	1.0	0.2	37	91.8	71.8
50	15	3.56	20	175	3.5	0.2	65	98.7	88.0
53	16	3.56	20	250	12.5	5.4	94	99.2	93.3
54	14	3.56	50	250	25.0	6.1	37	81.5	70.6
55	10	3.56	50	175	12.5	3.2	26	69.8	56.6
55	18	3.56	50	100	4.2	1.3	15	46.8	31.6
57	19	7.12	50	175	14.0	3.5	26	68.1	51.9
57	27	7.12	50	100	4.3	1.3	15	30.5	22.9
60	21	7.12	35	250	17.7	6.2	53	96.4	73.4
60	22	7.12	35	100	3.5	1.3	21	60.2	50.7
60	26	7.12	35	175	10.5	3.6	37	84.6	69.3
61	24	7.12	20	175	8.2	3.4	65	98.4	84.2
61	20	7.12	20	100	3.6	1.3	37	90.0	66.2
62	25	7.12	20	250	12.5	5.5	94	99.2	89.7
63	23	7.12	50	250	>25.0	5.9	37	76.3	68.1
64	22	7.12	35	100	3.7	1.2	21	66.1	49.2
64	25	7.12	20	250	11.8	5.1	94	99.3	86.7
69	2r	1.78	20	100	2.0	1.2	37	89.5	65.1
71	1r	1.78	50	175	9.5	4.2	26	73.6	54.3
71	9r	1.78	50	100	3.0	1.3	15	35.2	13.9
71	5r	1.78	50	250	17.0	8.5	37	86.5	67.4
72	8r	1.78	35	175	7.0	3.7	37	86.4	61.8
72	3r	1.78	35	250	12.8	6.6	53	94.4	76.9
72	7r	1.78	20	250	3.5	0.2	94	98.4	89.1
72	6r	1.78	20	175	2.5	0.1	65	97.8	84.1
72	4r	1.78	35	100	1.0	0.1	21	54.4	33.5
74	X1	1.78	20	290	4.0	0.1	108	99.1	91.4
74	X2	1.78	10	300	2.5	0.0	224	99.6	96.6

\* Alpha=D is equivalent to alpha =1.78 with the topmost and bottom most baffles removed

recorded and all samples were collected. During a typical air-stripping test, the samples were collected from inlet air, outlet air, inlet water, and outlet water streams.

Four tower *profile* stripping tests also were performed. During these tests, three additional water samples were collected from the sampling ports at different heights on the sides of the towers. These samples were used for tower concentration profile determinations.

After collection of samples and recording of the operating conditions, either the system was shut down for the day or the system parameters were changed to the next set of test conditions.

#### 4. Bacterial Growth

During operation of the air-stripping system, a bacterial growth was encountered in both the CCAS and CFAS towers. This gelatinous growth accumulated on the packing and caused the pressure drop across the towers to increase significantly over time. After the third series of tests (Day 64), the packing from both towers was taken out and *cleaned* with a high-pressure water spray. The packing was then placed back into the towers.

### B. STRIPPING TEST RESULTS AND DISCUSSION

#### 1. Air Stripping Tests

Air-stripping tests were performed using four baffle configurations. Nine runs were performed for each baffle configuration. All runs were completed for each baffle configuration before changing to the next configuration. Table 3 summarizes the test results. Raw data describing the physical observations made during the tests are shown in Appendix A. Table 3 displays only the concentration data for DCA, which was the main contaminant of interest. Other minor contaminant concentration data are shown in Appendix B. Table 3 also illustrates the pressure drops measured across the towers during each test. The air-to-water ratio, defined as the volumetric flow rate of air divided by the volumetric flow rate of water, is shown in the eighth column. The percent removal of DCA for each tower configuration is presented in columns nine (for CCAS) and ten (for CFAS).

Figures 13, 14, 15, and 16 present graphically the percent removal of DCA as a function of air flow rate for each of the four baffle configurations. As shown in these plots, stripping efficiency is increased as the air flow rate is increased at a constant water flow rate. The plots also indicate that stripping efficiency is greater at lower water flow rates (for higher air-to-water ratios). For similar operating conditions (air flow and water flow), the stripping efficiency of the CCAS tower is always greater than the stripping efficiency of the CFAS tower.

Figures 17 and 18 show the relationship between stripping efficiency and air-to-water ratio for the CFAS and CCAS towers. As the *air-to-water ratio* increases, the stripping efficiency increases for both towers, as is typical for packed tower air strippers. Larger air-to-water ratios increase stripping efficiency. As shown in Figure 17, the baffle configuration has very little effect on DCA stripping efficiency, especially at high air-to-water ratios. At lower air-to-water ratios, there appears to be some variability (Figure 17) in stripping efficiency for the different baffle configurations. However, this variability is random and is also noticed in Figure 18 for the CCAS tower at low air-to-water ratios. This indicates that the baffle configuration has little effect on stripping efficiency. The independence of stripping efficiency and baffle spacing also was noticed by Wood et al. (1990).



# Stripping Efficiency for DCA

Alpha D

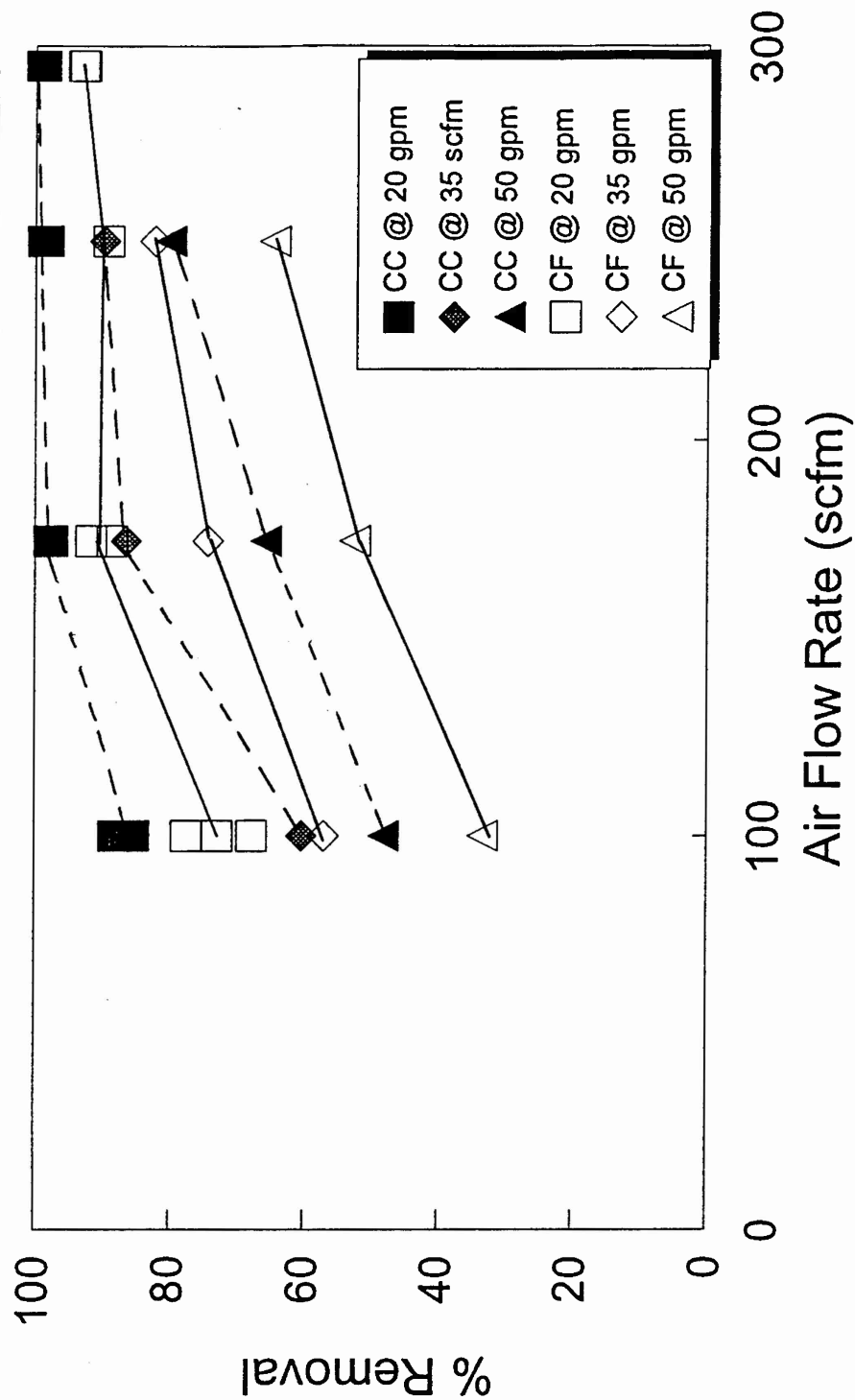


Figure 13. Stripping Efficiency of DCA as a Function of Air Flow Rate for Baffle Configuration  $\alpha = D$ .

# Stripping Efficiency for DCA

Alpha 1.78

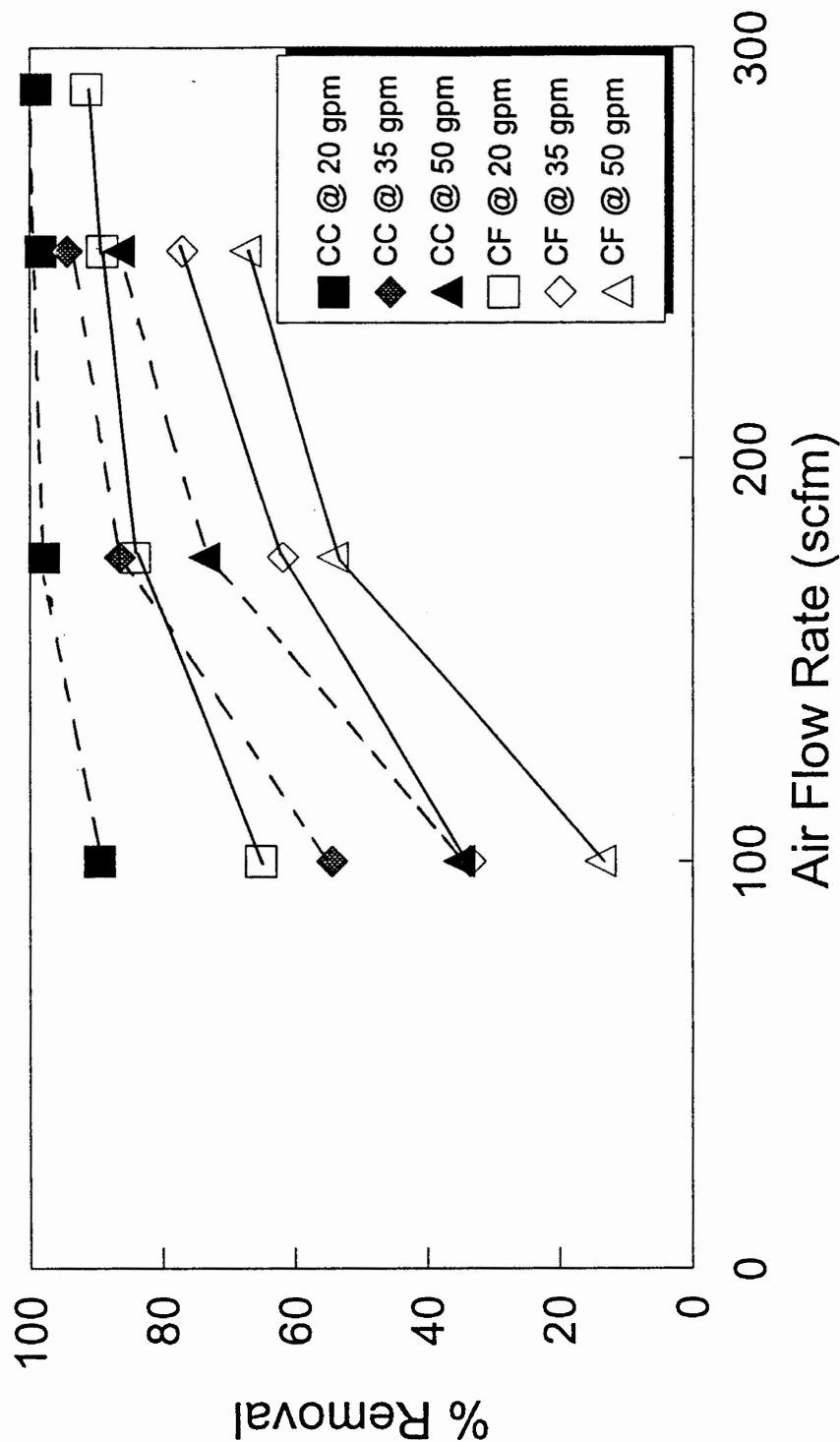


Figure 14. Stripping Efficiency of DCA as a Function of Air Flow Rate for Baffle Configuration  $\alpha = 1.78$ .

# Stripping Efficiency for DCA

Alpha 3.56

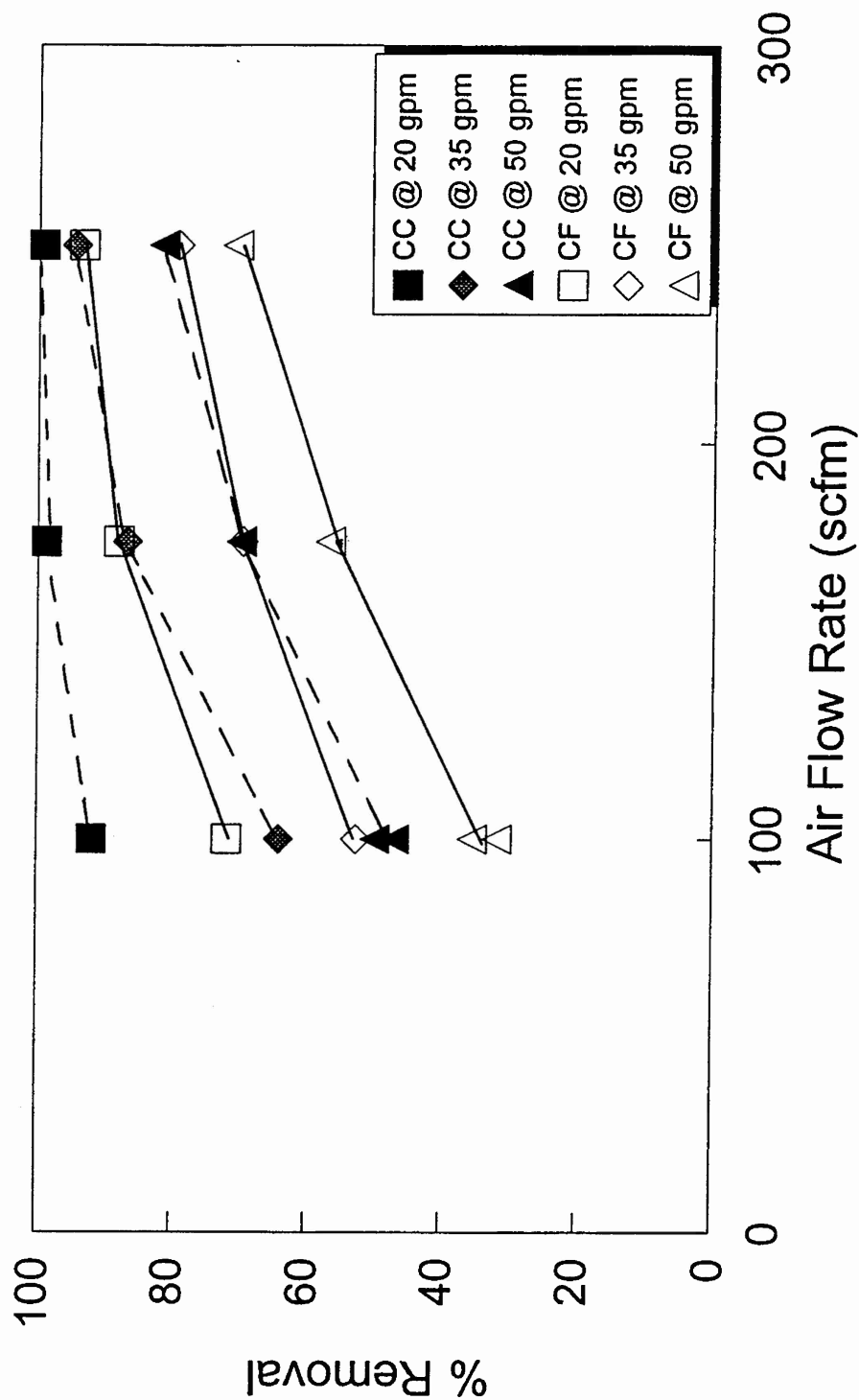


Figure 15. Stripping Efficiency of DCA as a Function of Air Flow Rate for Baffle Configuration  $\alpha = 3.56$ .

# Stripping Efficiency for DCA

Alpha 7.12

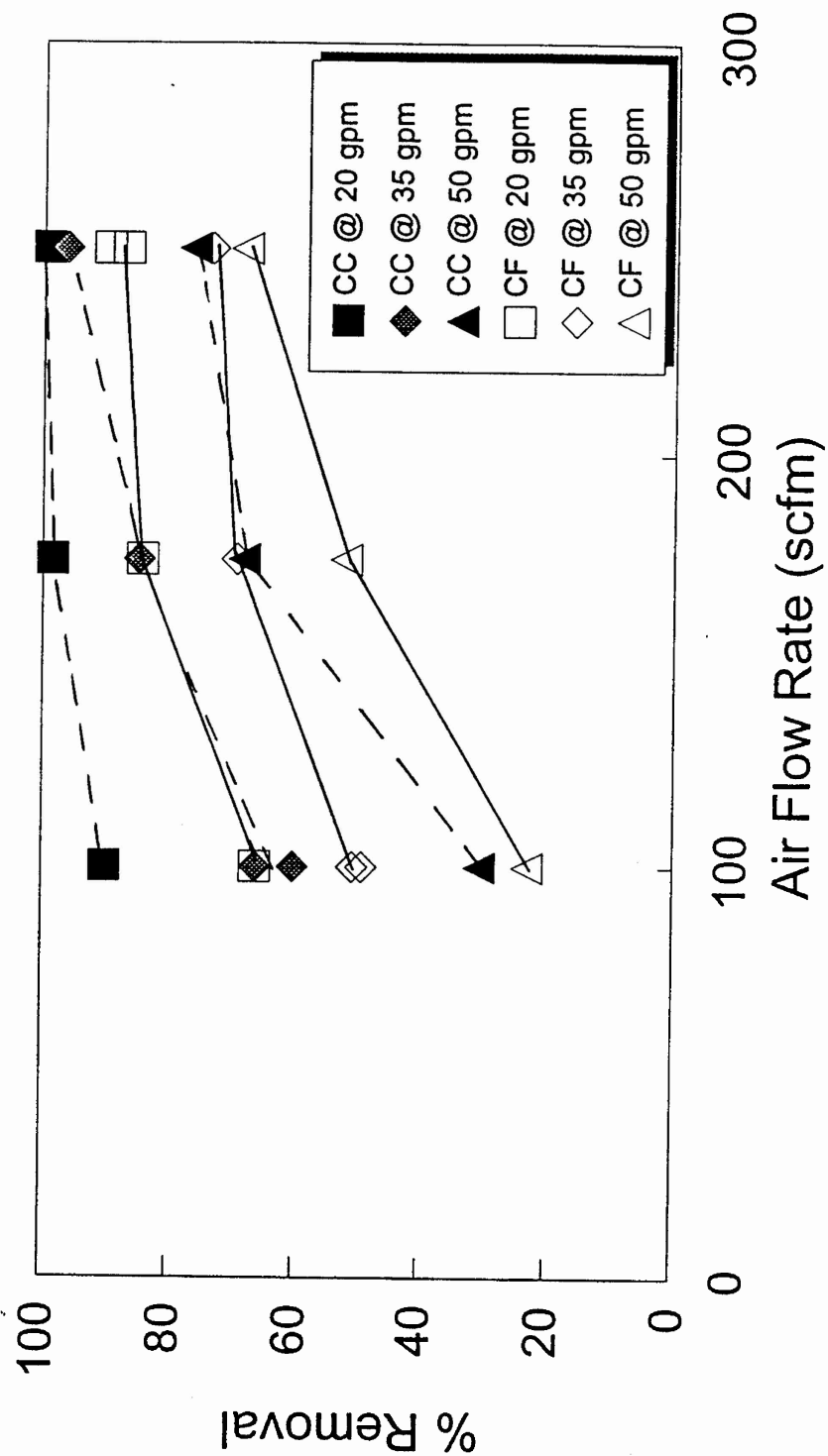


Figure 16. Stripping Efficiency of DCA as a Function of Air Flow Rate for Baffle Configuration  $\alpha = 7.12$ .

# Dichloroethane-Stripping Efficiency

Crossflow Tower

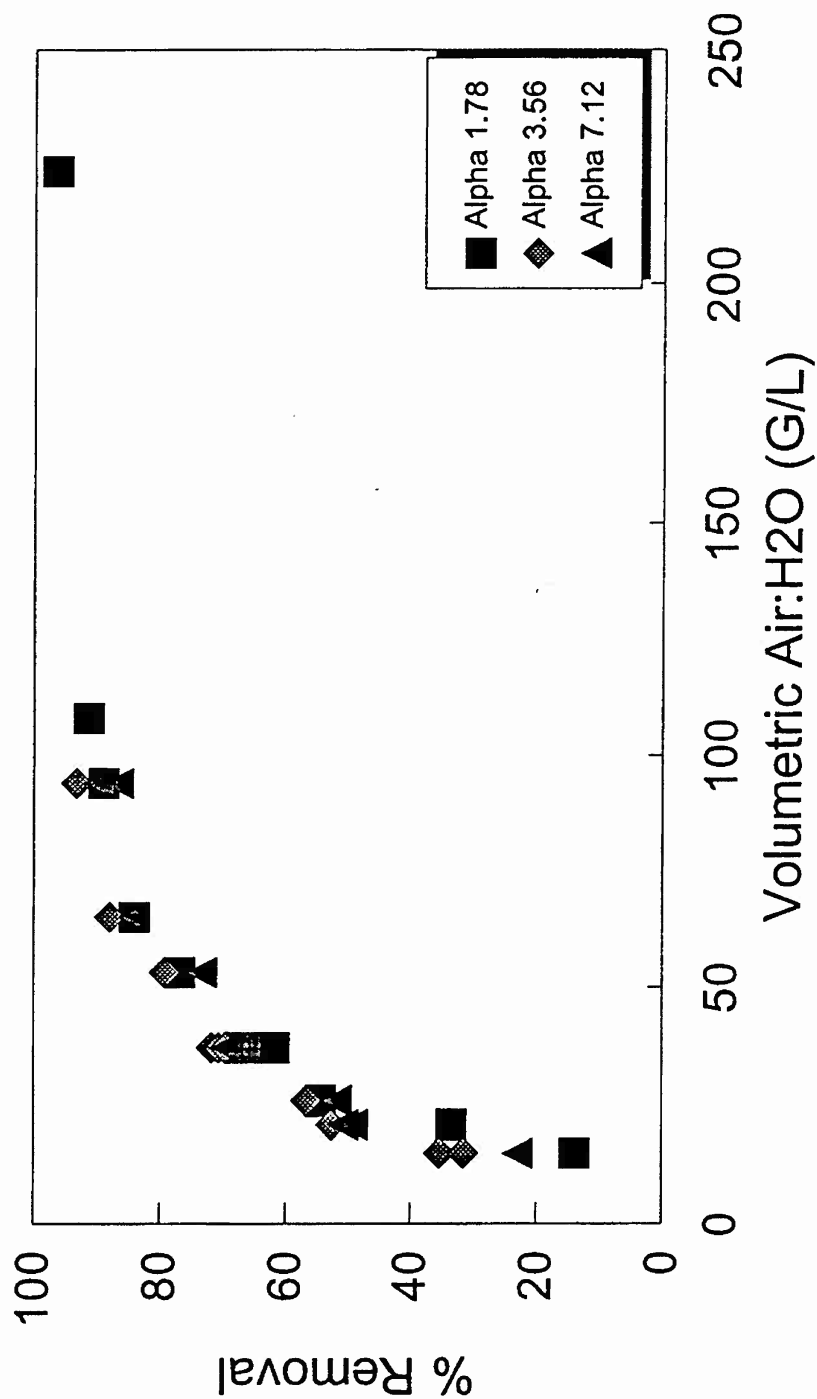


Figure 17. Stripping Efficiency of DCA as a Function of Air-to-Water Ratio for Three Crossflow Air-Stripping Tower Configurations.

# Dichloroethane-Stripping Efficiency

## Countercurrent Tower

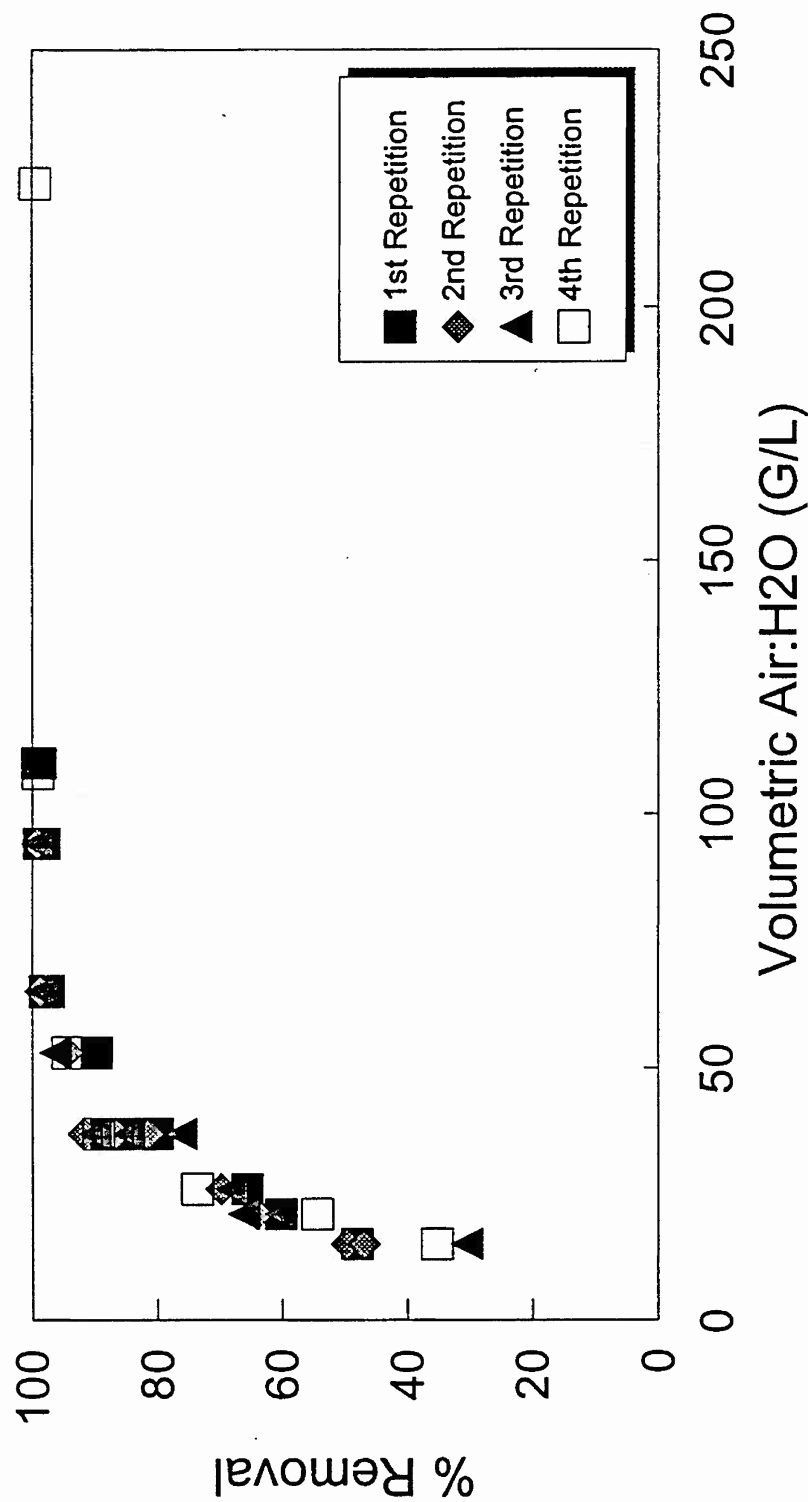


Figure 18. Replicate Determinations of Stripping Efficiency of DCA as a Function of Air-to-Water Ratio for the Countercurrent Air-Stripping Tower.

Appendix C presents a statistical analysis performed on the data to identify correlations and differences. Strong correlations were found between stripping efficiency and air flow rate, water flow rate, and air-to-water ratio, as was expected. The pressure drop was found to be strongly correlated to air flow rate and time. The time factor indicates that the pressure drop in both towers increased as the days passed because of microbial fouling. This microbial fouling effect made evaluation of the pressure drop data somewhat difficult by introducing a new factor that affects pressure drop.

Figure 19 compares the DCA *stripping efficiencies* of the CCAS and CFAS towers at identical operating conditions. The stripping efficiency of the CCAS tower is slightly greater than that of the CFAS tower at identical air-to-water ratios. Higher air-to-water ratios are required in the CFAS tower to obtain the same stripping efficiency. Table 3 shows that the higher air-to-water ratio required in the CFAS tower to obtain a CCAS-equivalent stripping efficiency can be achieved while still keeping the CFAS pressure drop below that in the CCAS tower. For example, a comparison of Tests 2r and 7r in Table 3 indicates that approximately 90 percent stripping efficiency can be achieved in both towers by operating the CCAS tower at an air-to-water ratio of 37 and the CFAS tower at an air-to-water ratio of 94. The concomitant pressure drops are 2.0 inches and 0.2 inch water in the CCAS and CFAS towers, respectively. In other words, the same stripping efficiency can be achieved in both towers while using less energy input to the blower in the CFAS tower. This also was confirmed during the extended test (Section VI).

## 2. Profile Tests

Four tests were performed to observe the relationship between packing depth (meters) and stripping efficiency (percent). Water samples from various packing depths (at various depths in the tower) were collected and analyzed. Figures 20 and 21 illustrate the results for the CCAS and CFAS towers, respectively. In both figures, the x coordinate is a function of the packed height (z) and the y coordinate is a function of the ratio  $C_z/C_2$ , where  $C_z$  is the DCA concentration in the water at depth z and  $C_2$  is the tower outlet water concentration. The water flow rate (L), air flow rate (G), tower cross-sectional area (A), and air temperature (T) are the other parameters listed in the x and y coordinates. The symbols H and R represent the Henry's Law constant and the universal gas constant, respectively.

The x and y coordinates are selected such that the slope of the line joining these points represents the overall mass transfer coefficient (Gross and TerMaath, 1985). The units of the x coordinate are time (minutes); the y coordinate is dimensionless. For the CCAS tower (Figure 20), the slope is in the 0.418- to 0.538-min<sup>-1</sup> range. The slope for the CFAS tower is in the 0.170- to 0.318 min<sup>-1</sup> range for the four selected test conditions. Further discussion on mass transfer coefficients is included in Section VII.

## 3. Bacterial Growth

The gradual bacterial growth that accumulated on the packing in both towers caused the *pressure drop* across the towers to increase significantly. Figure 22 illustrates this effect for the CCAS tower at a water flow rate of 50 gpm. The packing was left in place for the first three series of experiments. As shown in Figure 22, the pressure drop at a given air flow rate increased significantly from the first, to the second, to the third repetition (over time). The packing was removed and cleaned before initiating the fourth series of experiments, and the pressure drops returned to approximately their initial values for this fourth series. Figure 23 illustrates the pressure drop characteristics of the CFAS tower for the three baffle configurations.

# Stripping Efficiency for DCA

## Comparison Between CFAS and CCAS Towers

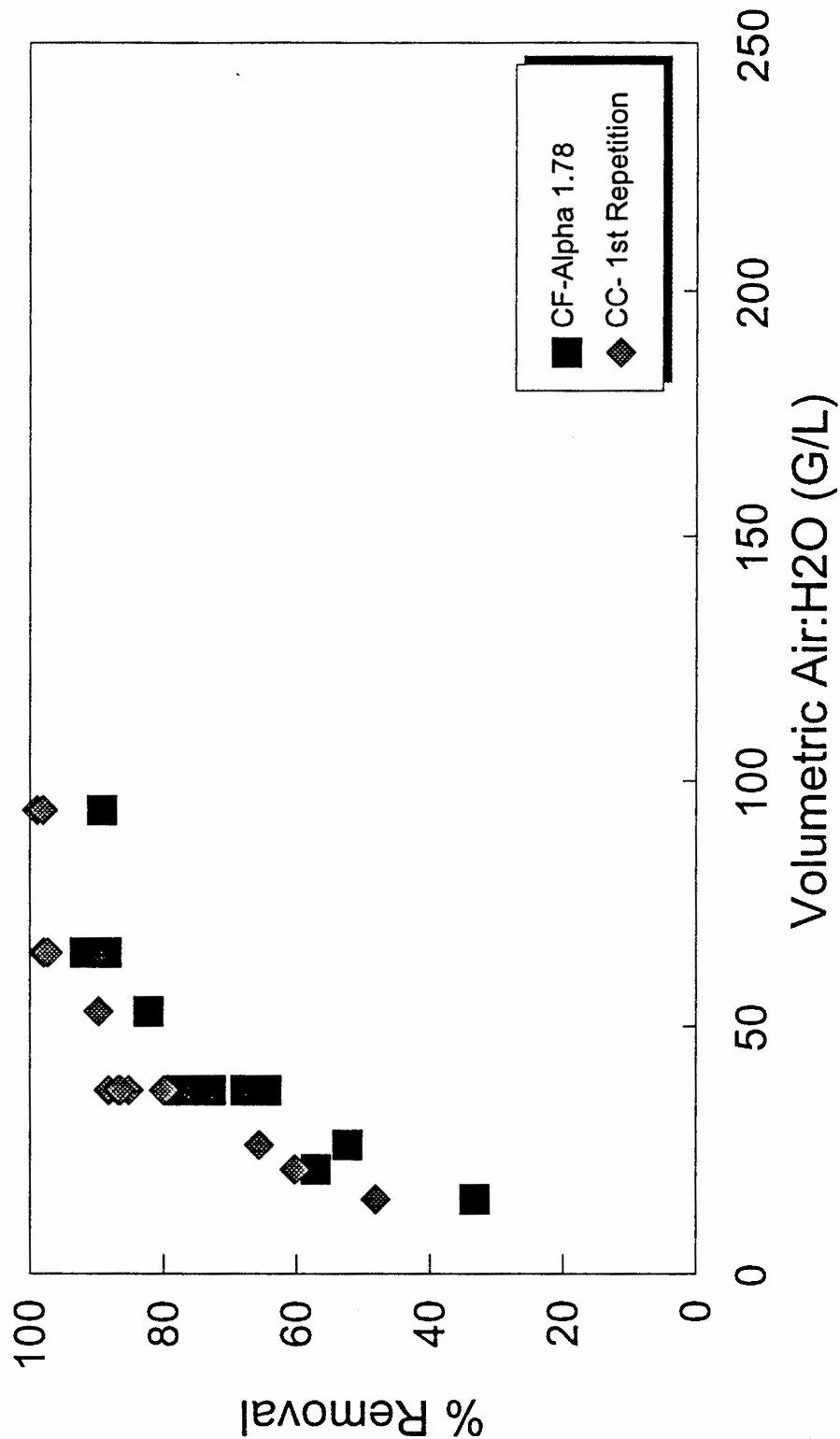


Figure 19. Comparison of Stripping Efficiency Between the Crossflow and Countercurrent Air-Stripping Tower Configurations.



# Mass Transfer Coefficient Determination Plot

## CCAS

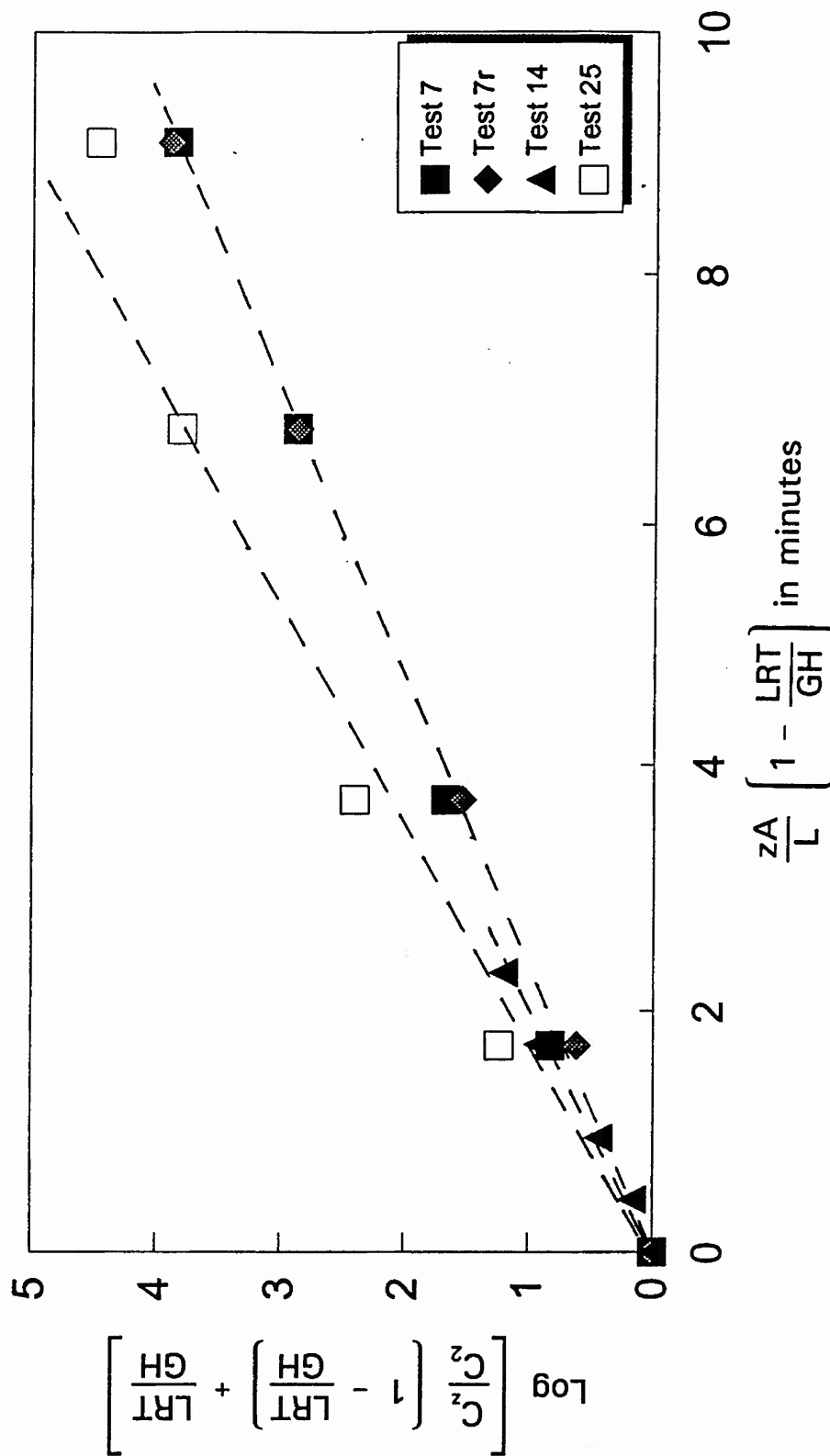


Figure 20. Effect of Packing Depth on Stripping Efficiency for the Countercurrent Tower.

# Mass Transfer Coefficient Determination Plot

CFAS

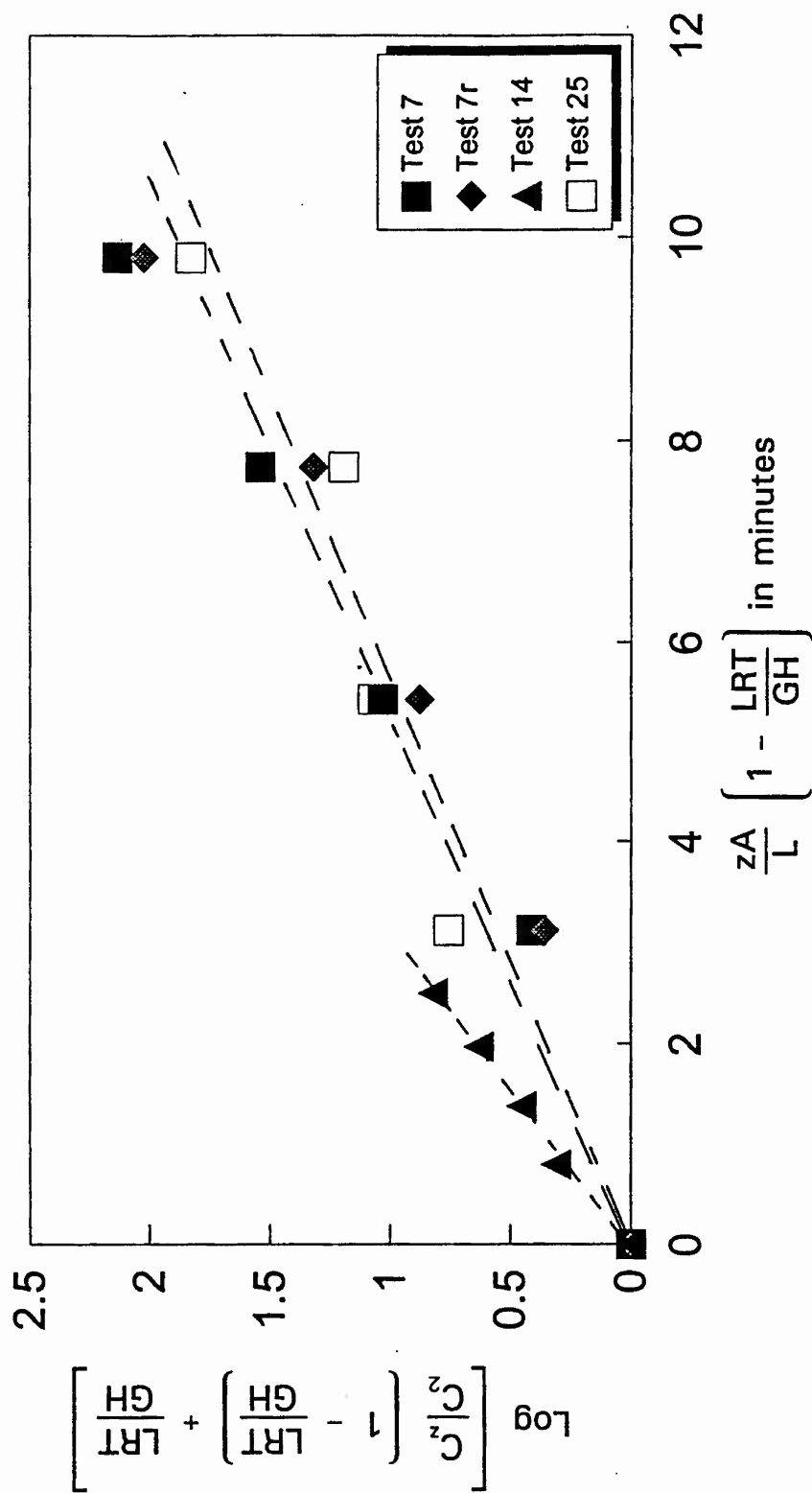


Figure 21. Effect of Packing Depth on Stripping Efficiency for the Crossflow Tower.

# Pressure Drop as a Function of Air Flow Rate Countercurrent Tower

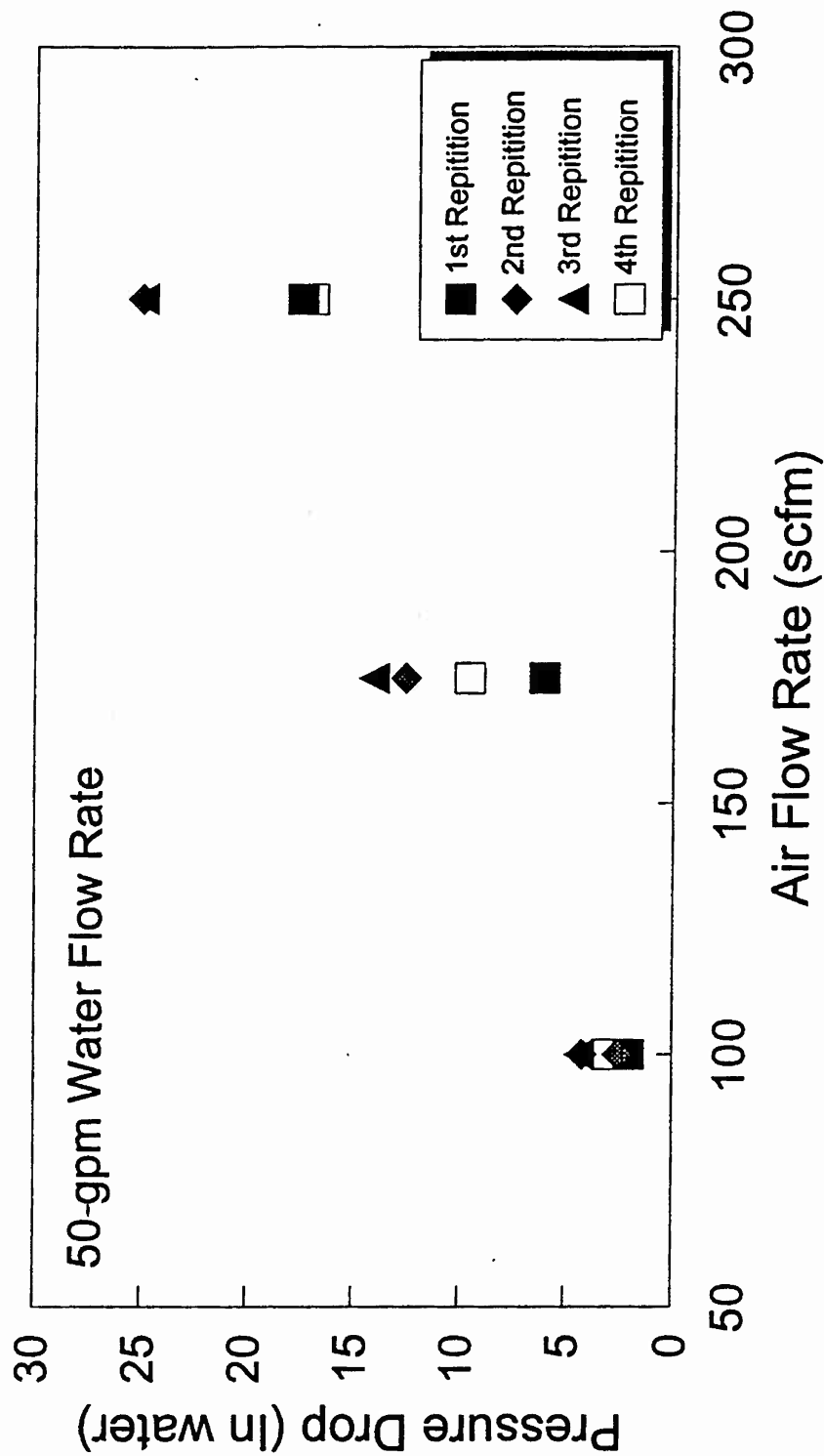


Figure 22. Pressure Drop through the Countercurrent Tower as a Function of Air Flow Rate and a 50-gpm Water Flow Rate.

# Pressure Drop as a Function of Air Flow Rate

Crossflow Tower

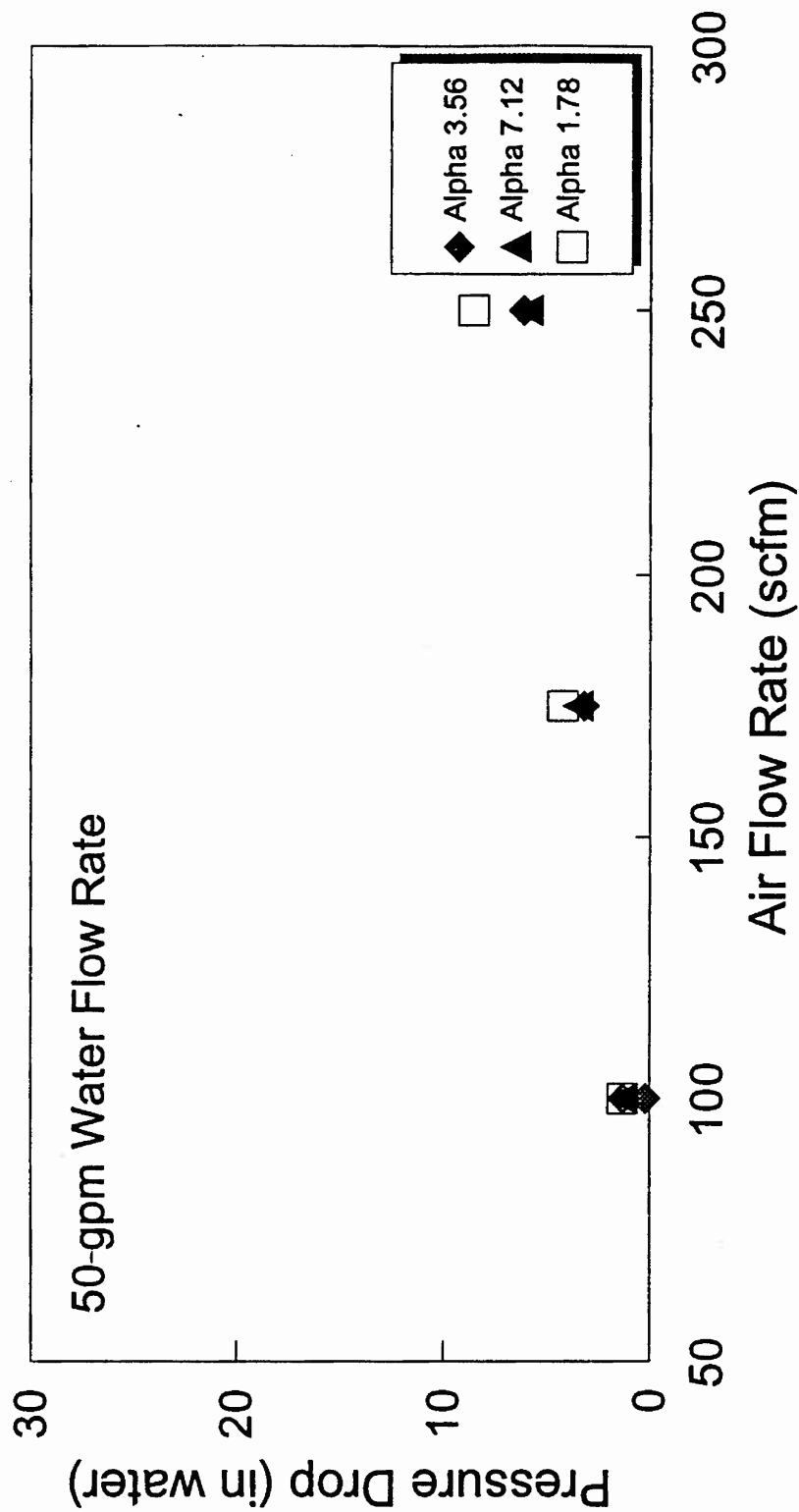


Figure 23. Pressure Drop through the Crossflow Tower as a Function of Air Flow Rate and a 50-gpm Water Flow Rate.

In the CFAS tower, the differences in pressure drops at the same air flow rate can be explained partly by the differences in baffle configurations and partly by the increase in bacterial growth over time. The bacterial growth effect is less significant, because the CFAS tower was opened (and the packing cleaned) during each baffle change. The configuration with the most *baffles* ( $\alpha = 1.78$ ) had the greatest pressure drop.

## SECTION V

### CATALYTIC OXIDATION TESTING — PRELIMINARY TEST

The catalytic oxidation preliminary test was conducted from August to November, 1993, along with the air stripping preliminary test.

#### A. DESCRIPTION

The catalytic oxidation tests were conducted simultaneously for five catalyst types at nine different test conditions each. Four of the catalysts were used in the *bench-scale fixed-bed reactors*, and the fifth was used in the *pilot-scale fluidized-bed reactor*. The four fixed-bed proprietary catalysts were provided by:

- University of Akron (UA)
- Haldor Topsoe, A/S (HT)
- Allied Signal, Inc. (AS)
- Salem Engelhard, Inc. (SE).

The UA and HT catalysts were bead catalysts, whereas the AS and SE catalysts were monolithic cylinders. Each catalyst was tested at *three temperatures* and *three space velocities*. The temperatures and space velocities were selected to bracket the optimum operating conditions specified by the catalyst manufacturers. The temperature range tested was 600 to 880°F for all the catalysts except the UA catalyst, for which the recommended maximum temperature was 800°F. Space velocities ranged from 2,500 to 10,000 hr<sup>-1</sup>.

The fifth catalyst (provided by ARI International, Inc.) was a fluidized-bed commercial catalyst placed in a 500-scfm-capacity pilot unit to oxidize the bulk of the airstream from the tower. However, this pilot unit had several startup problems due to faulty parts and the manufacturer was unable to bring it on line in a reasonable period of time. The testing of this catalyst was therefore abandoned. Because the low levels of VOCs in the airstream were below state regulatory limits for daily discharge, the bulk of the airstream was discharged into the ambient without treatment.

##### 1. Startup

After installation, the bench-scale catalytic oxidizers were switched on and brought up to temperature. The catalyst bed temperature was slowly increased to avoid overshooting the maximum recommended catalyst temperature. A clean ambient airstream was passed through the catalyst chambers during startup. This was necessary to avoid contaminating the catalysts with organic compounds before they reached the desired operating conditions. The catalytic units were left on for the duration of the catalyst test as a result of the long period of time necessary to bring them up to operating temperature.

##### 2. Process Description

The process airstreams from the CCAS and CFAS towers were combined and directed to the catalytic oxidation units. A small in-line booster blower was used to move 15 scfm of the process air to the bench-scale units; the remainder (approximately 485 scfm) was discharged to the ambient. Although the fixed-bed oxidizers required less than 1 scfm of process air for any test, 15 scfm was

needed to prevent the booster blower from overheating and shutting down. The excess portion of this feed airstream also was discharged to the ambient. The four fixed-bed catalytic oxidizers were operated in parallel. Rotameters were used to control the flow of air into each of the units. The treated (exiting) streams eventually were combined and vented through a common stack located outside of the trailer.

The catalytic system was equipped with five sampling ports for collection of gas samples. One port was located in the 15-scfm process airstream to the catalysts and the remaining four were located at the outlet of each catalyst.

### 3. Operation and Sampling

Air samples were collected after the stripping system reached steady-state. Water and air samples initially were collected from the CCAS and CFAS process streams to ensure that the stripping system was operating properly. During each catalyst test run, an ambient air sample, a catalyst *inlet* air sample (one sample common to all catalysts), and *outlet* air samples (one sample at the outlet of each catalyst) were collected. Each sample had to be analyzed before collection of the next sample. Hence, there was an approximate 3- to 4-hour time span between collecting the initial and final samples. To verify that the inlet process air concentration had not changed significantly during the test-run period, an inlet sample (to the catalytic units) was generally collected at both the beginning and the conclusion of the 3- to 4-hour test-run period and averaged for the run.

## B. RESULTS

The operating conditions for the catalytic oxidation tests for DCA are displayed in Table 4. Appendix D describes the physical test conditions for the preliminary test. Appendix E shows the destruction data for the minor contaminants. The destruction efficiencies observed for DCA are shown in Table 5. At the most aggressive test condition (Test 09r), which was  $2,500\text{-hr}^{-1}$  space velocity and  $880^{\circ}\text{F}$  temperature, all four catalysts achieved more than 99 percent destruction. The data are plotted in Figures 24, 25, and 26. For each plot, the percent destruction was graphed as a function of temperature at a constant space velocity. Temperature strongly affected destruction efficiency, as expected. Generally, the higher the space velocity (i.e., the shorter the residence time), the lower was the destruction efficiency, although this effect was not very pronounced in the test range. The UA catalyst appeared to have a slightly higher destruction efficiency than the other catalysts for the range of test conditions evaluated during the preliminary test. The statistical analysis (Appendix C) also appears to indicate a slightly higher destruction efficiency for the UA catalyst. However, in general, all four catalysts performed well, with all four demonstrating more than 99 percent removal at the most aggressive conditions recommended by the manufacturers.

TABLE 4. OPERATING CONDITIONS AND RESULTS FOR CATALYST TESTING

Test ID	Date	Catalyst Type*	Nominal Temp (F)	Space Velocity (hr <sup>-1</sup> )	Air Flow Rate (cfm)	Average Inlet DCA Conc. (ppbv)	Outlet DCA Conc. (ppbv)
3	10/04/93	UA	800	5000	0.151	4579	53
3	10/04/93	HT	880	5000	0.151	4579	106
3	10/04/93	AS	880	5000	0.151	4579	123
3	10/04/93	SE	880	5000	0.114	4579	51
9	10/05/93	UA	800	2500	0.075	3932	22
9	10/05/93	HT	880	2500	0.075	3932	54
9	10/05/93	AS	880	2500	0.075	3932	94
9	10/05/93	SE	880	2500	0.057	3932	19
6	10/06/93	HT	880	10000	0.302	3631	456
6	10/06/93	UA	800	10000	0.302	3631	38
6	10/06/93	SE	880	10000	0.227	3631	134
6	10/06/93	AS	880	10000	0.302	3631	276
8	10/07/93	UA	740	10000	0.302	3642	73
8	10/07/93	HT	740	10000	0.302	3642	888
8	10/07/93	AS	740	10000	0.302	3642	440
8	10/07/93	SE	740	10000	0.227	3642	179
5	10/08/93	UA	740	5000	0.151	3883	62
5	10/08/93	HT	740	5000	0.151	3883	710
5	10/08/93	AS	740	5000	0.151	3883	400
5	10/08/93	SE	740	5000	0.114	3883	163
2	10/11/93	UA	740	2500	0.075	3167	57
2	10/11/93	SE	740	2500	0.057	3167	71
2	10/11/93	HT	740	2500	0.075	3167	136
2	10/11/93	AS	740	2500	0.075	3167	276
4	10/12/93	UA	600	2500	0.075	4180	170
4	10/12/93	HT	600	2500	0.075	4180	754
4	10/12/93	AS	600	2500	0.075	4180	570
4	10/12/93	SE	600	2500	0.057	4180	262
7	10/12/93	UA	600	5000	0.151	4349	632
7	10/12/93	SE	600	5000	0.114	4349	724
7	10/12/93	HT	600	5000	0.151	4349	1245
7	10/12/93	AS	600	5000	0.151	4349	709
1	10/13/93	UA	600	10000	0.302	4794	1116
1	10/13/93	HT	600	10000	0.302	4794	1798
1	10/13/93	SE	600	10000	0.227	4794	1222
1	10/13/93	AS	600	10000	0.302	4794	1242
09r	11/11/93	UA	800	2500	0.075	5227	20
09r	11/11/93	SE	880	2500	0.057	5227	2
09r	11/11/93	AS	880	2500	0.075	5227	2
09r	11/11/93	HT	880	2500	0.075	5227	2
04r	11/12/93	SE	600	2500	0.057	5275	193
09rr	11/12/93	HT	880	2500	0.075	5275	2
02r	11/12/93	SE	740	2500	0.057	5275	32

\*UA - University of Akron  
HT- Haldor Topsoe  
AS - Allied Signal  
SE - Salem Engelhard



TABLE 5. DESTRUCTION EFFICIENCY OF CATALYSTS

Test ID	Catalyst*	Bed Temp (F)	Space Velocity (hr <sup>-1</sup> )	Destruction Efficiency (% Removed)
3	UA	800	5000	98.8
3	HT	880	5000	97.7
3	AS	880	5000	97.3
3	SE	880	5000	98.9
9	UA	800	2500	99.4
9	HT	880	2500	98.6
9	AS	880	2500	97.6
9	SE	880	2500	99.5
6	HT	880	10000	87.4
6	UA	800	10000	99.0
6	SE	880	10000	96.3
6	AS	880	10000	92.4
8	UA	740	10000	98.0
8	HT	740	10000	75.6
8	AS	740	10000	87.9
8	SE	740	10000	95.1
5	UA	740	5000	98.4
5	HT	740	5000	81.7
5	AS	740	5000	89.7
5	SE	740	5000	95.8
2	UA	740	2500	98.2
2	SE	740	2500	97.8
2	HT	740	2500	95.7
2	AS	740	2500	91.3
4	UA	600	2500	95.9
4	HT	600	2500	82.0
4	AS	600	2500	86.4
4	SE	600	2500	93.7
7	UA	600	5000	85.5
7	SE	600	5000	83.4
7	HT	600	5000	71.4
7	AS	600	5000	83.7
1	UA	600	10000	76.7
1	HT	600	10000	62.5
1	SE	600	10000	74.5
1	AS	600	10000	74.1
09r	UA	800	2500	99.6
09r	SE	880	2500	100.0
09r	AS	880	2500	100.0
09r	HT	880	2500	100.0
04r	SE	600	2500	96.3
09rr	HT	880	2500	100.0
02r	SE	740	2500	99.4

\*UA - University of Akron  
HT- Haldor Topsoe  
AS - Allied Signal  
SE - Salem Engelhard

# Catalyst Destruction Efficiency 2500 hr-1 Space Velocity

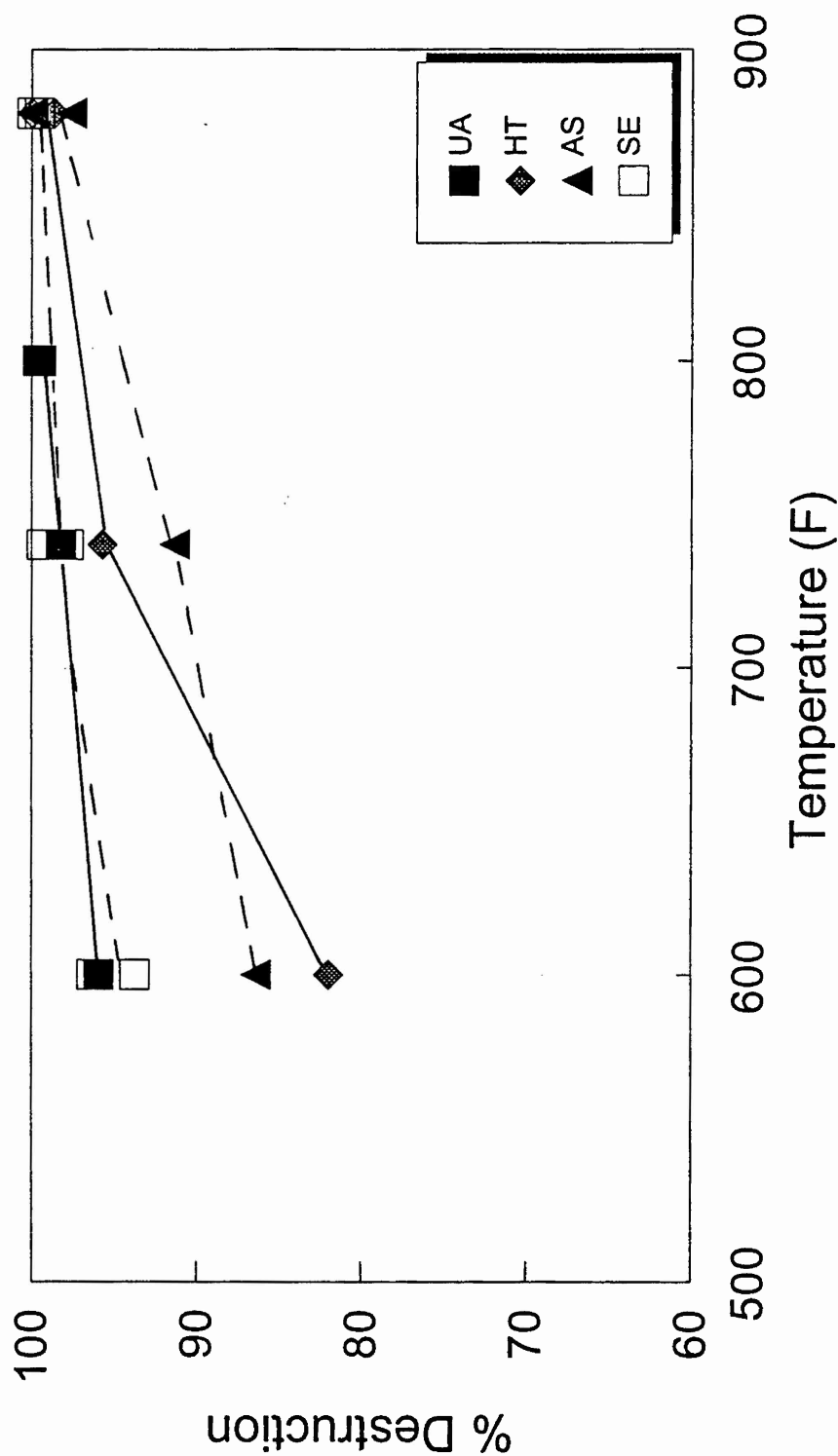


Figure 24. Destruction Efficiency of Catalysts at 2,500 hr<sup>-1</sup> Space Velocity.

# Catalyst Destruction Efficiency 5000 hr-1 Space Velocity

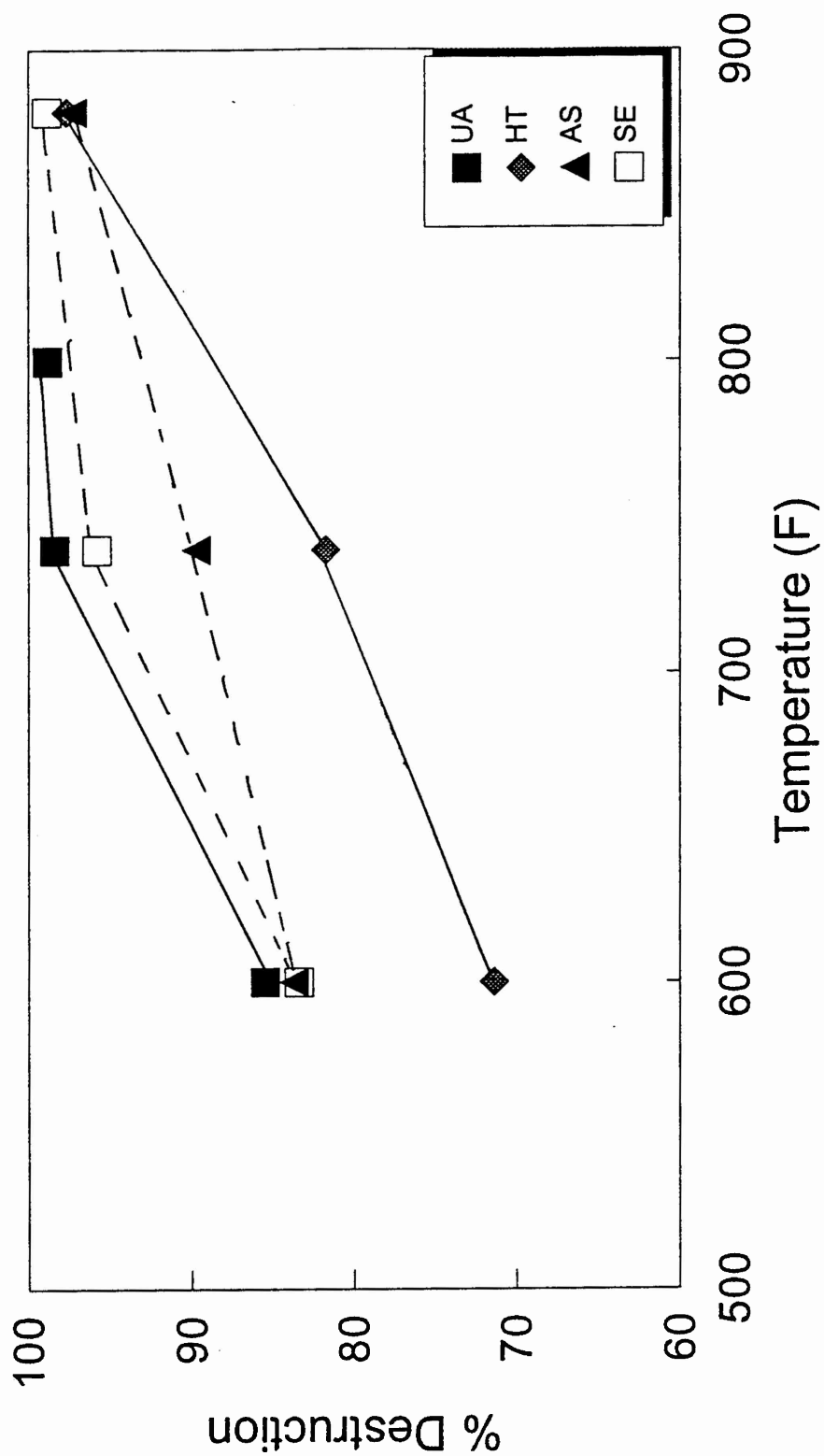


Figure 25. Destruction Efficiency of Catalysts at 5,000 hr<sup>-1</sup> Space Velocity.

## Catalyst Destruction Efficiency 10000 hr<sup>-1</sup> Space Velocity

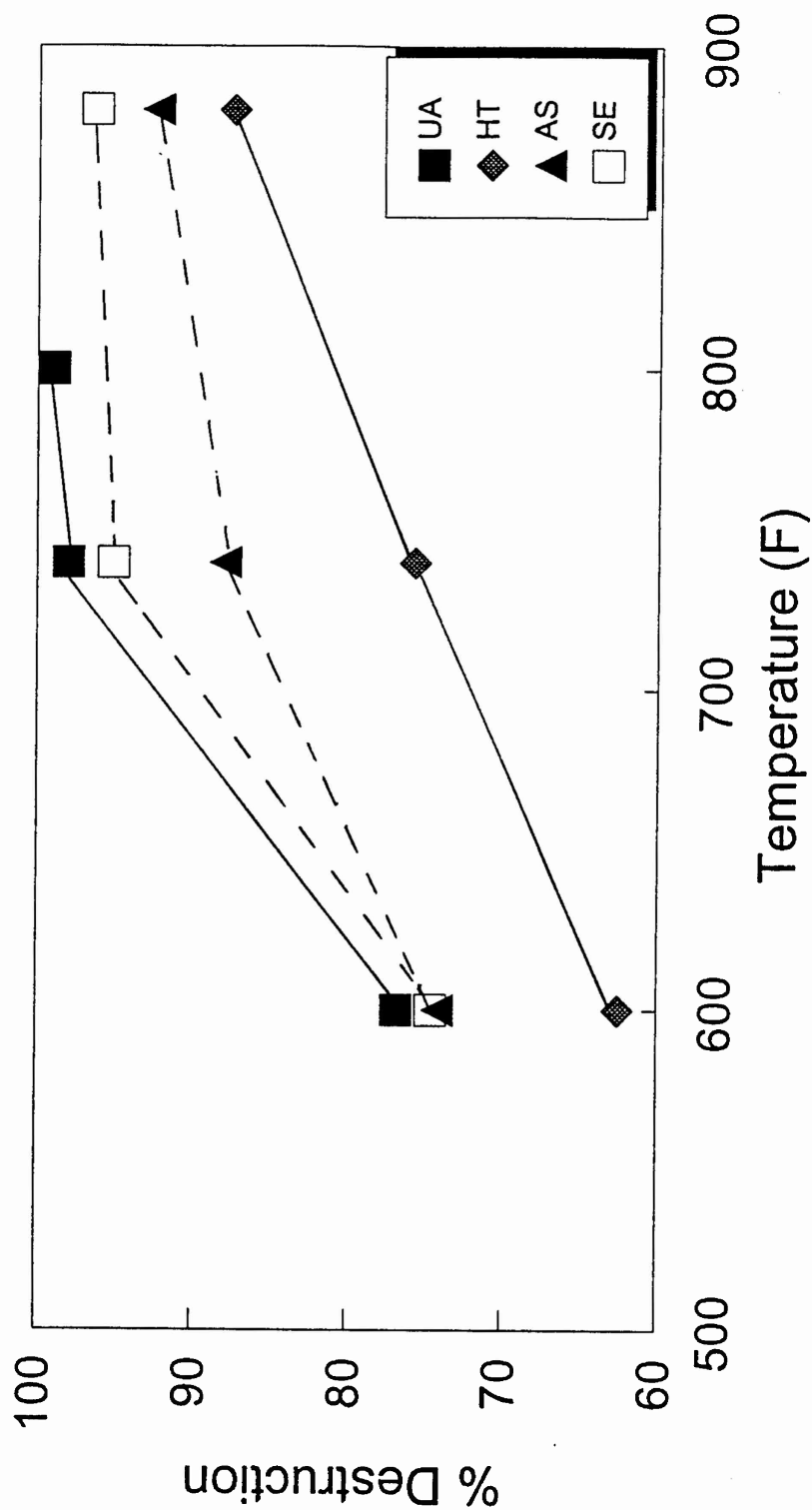


Figure 26. Destruction Efficiency of Catalysts at 10,000 hr<sup>-1</sup> Space Velocity.

## SECTION VI EXTENDED TEST

### A. DESCRIPTION

An extended test was conducted on the air-stripping towers and catalytic oxidizers. The test was performed continuously over 10 weeks. The purpose of this test was to compare the efficiencies of the CFAS and the CCAS towers, as well as the efficiencies of the catalysts tested under *continuous steady-state* conditions. The groundwater was spiked with DCA, resulting in groundwater concentrations of approximately 1 ppm. Pretreatment of the groundwater with sodium citrate was *eliminated* during the extended test. This was done in part to allow the evaluation of the effect of iron precipitation on the performance of the air strippers. The other reason was that the citrate was suspected of contributing to the microbial fouling noticed during the preliminary test. In addition, iron levels in the groundwater from the extraction wells were found to be much lower toward the end of the preliminary test than was observed in the monitoring wells at the beginning. The objective of the extended test was to monitor the performance of the two towers and the catalytic units, and to identify any problems that might arise during continuous operation.

The CFAS tower was tested using 9 baffles ( $\alpha = 1.78$ ). Both towers were operated at a 20-gpm water flow rate. The air flow rates were selected so as to achieve 95 percent removal of DCA in each tower. The crossflow tower, therefore, was operated at 250 scfm (air-to-water ratio of 94), and the countercurrent tower was operated at 160 scfm (air-to-water ratio of 60). These air flow rates gave *identical removal efficiencies* in both towers.

Four bench-scale fixed-bed catalysts were tested during the extended test. An experimental catalyst (X), was tested in place of the HT catalyst. Catalyst X was a bead catalyst composed of first row transition metal oxides on a proprietary support material. A *pilot-scale photocatalytic oxidizer* supplied by KSE, Inc. was tested as a replacement for the ARI fluidized-bed incinerator.

Based on the results of the preliminary test, the bench-scale catalysts were operated at approximately 0.1 scfm (*space velocity* of 5,000 hr<sup>-1</sup>). Based on the manufacturer's recommendation, the pilot-scale photocatalytic oxidizer was operated at an air flow rate of 50 to 55 scfm (*space velocity* of 1,237 to 1,145 hr<sup>-1</sup>). For the bench-scale catalysts, bed *temperatures* were selected to obtain the maximum conversion of DCA based on the results of the preliminary test. The AS and SE catalysts were operated at 880°F and the UA catalyst was operated at 800°F. Catalyst X was experimental and was tested at a broad range of temperatures from 480 to 638°F. A fresh charge of catalyst was placed into each of the fixed-bed reactors at the beginning of the extended test.

#### 1. Photocatalytic Oxidizer

The photocatalytic oxidizer employs a technology called the Adsorption-Integrated-Reaction (AIR) process. It uses a proprietary catalyst in conjunction with banks of ultraviolet (UV) lights. The lights activate the oxygen present in the airstream, which in turn oxidizes the contaminants. The pilot-scale unit was designed by KSE to achieve 95 percent destruction of DCA at an air flow rate of 50 scfm. The unit employs a preheater to heat the inlet airstream, thereby reducing its relative humidity. The preheater was operated in the *temperature range* of 165 to 180°F. The heated air passes through the reactor, consisting of a catalyst bed illuminated with UV lamps. Thirty-four UV lamps were needed to obtain approximately 95 percent conversion.

## B. OPERATION AND SAMPLING

The treatment system (towers and catalytic oxidizers) was operated as described in Section 4.A.3, and operated continuously for 10 weeks. The first set of samples was taken 24 hours after bringing the system on line. A minimum of two sets of samples were analyzed each week. A typical set consisted of *inlet and outlet air* samples from each tower, *inlet and outlet water* samples from each tower, a *common inlet air* sample before the catalysts, and *outlet air* samples after each catalyst. In addition, calibration standards and duplicate samples were analyzed daily to verify the accuracy of the results.

Air and water flow rates were monitored daily. The system flow rates, temperatures, and pressures were recorded on the same days that the samples were collected.

## C. RESULTS

### 1. Air Stripping Test

The air strippers were operated for 10 weeks. The crossflow tower was operated with 9 baffles ( $\alpha = 1.78$ ). Table 6 presents the air stripping results for DCA. Raw data collected during this extended test are shown in Appendix A. The stripping results for the minor contaminants are shown in Appendix B.

The results are summarized graphically in Figures 27 and 28. It is seen that both the *stripping efficiency* and *pressure drop* across each tower remained relatively *constant* throughout the duration of the test. The average stripping efficiency over the 10-week period was 96.4 percent for the CCAS tower and 94.4 percent for the CFAS tower. However, the pressure drop in the CFAS tower was an *order of magnitude lower* than in the CCAS tower.

#### a. Fouling

The *consistent* nature of the operation, with regard to stripping efficiency and pressure drop, indicates that *microbial fouling* was not a major concern at this site. The tower packing (1-inch plastic Pall rings) was removed from the stripping towers at the completion of the extended test. This packing was covered with a very thin film of reddish-brown iron oxide. However, there was no evidence of the gelatinous microbial growth that was encountered during the preliminary test. Sodium citrate added during the preliminary test likely accelerated the development of microbial colonies. The elimination of sodium citrate does, however, appear to increase the possibility of *iron fouling* over the long term. Over a longer time (6 months or more), it is likely that the iron fouling would affect the performance of the stripping towers.

### 2. Catalytic Oxidation

#### a. Bench-Scale Catalysts

Table 7 presents the results of the oxidation test for the UA, AS, and SE catalysts. Appendix C describes the physical test conditions for the extended test. The DCA results are depicted graphically in Figure 29. The catalysts showed no signs of deactivation during the 10-week test period. The average oxidation efficiency of the AS and SE catalysts was greater than 99 percent throughout. The UA catalyst had an average oxidation efficiency of approximately

**TABLE 6. AIR-STRIPPING TOWER RESULTS FOR EXTENDED TEST**

Date	Day	Pressure Drop (inches water)		Removal Efficiency (%)	
		CC	CF	CC	CF
05/11/94	1	1.5	0.2	0.95	0.96
05/12/94	2	1.8	0.1	0.95	0.94
05/13/94	3	1.9	0.1	0.97	0.95
05/15/94	5	1.5	0.2	0.95	0.93
05/17/94	7	2.0	0.2	0.97	0.94
05/19/94	9	2.0	0.2	0.97	0.94
05/23/94	13	1.8	0.2	0.96	0.94
05/24/94	14	1.8	0.2	0.96	0.93
05/25/94	15	1.8	0.2	0.96	0.93
05/27/94	17	2.0	0.2	0.97	0.93
05/31/94	21	2.5	0.2	0.96	0.91
06/01/94	22	1.9	0.2	0.95	0.92
06/10/94	31	1.8	0.2	0.96	0.94
06/12/94	33	1.8	0.2	0.96	0.95
06/13/94	34	1.8	0.2	0.96	0.95
06/15/94	36	1.8	0.2	0.96	0.94
06/17/94	38	1.8	0.2	0.96	0.94
06/19/94	40	1.8	0.2	0.97	0.95
06/22/94	43	1.8	0.2	0.97	0.95
06/23/94	44	1.5	0.2	0.97	0.95
06/28/94	49	1.8	0.2	0.97	0.96
06/30/94	51	1.9	0.2	0.97	0.96
07/02/94	53	1.8	0.2	—	0.96
07/04/94	55	1.8	0.2	0.95	0.93
07/07/94	58	1.8	0.2	0.96	0.95
07/12/94	63	1.8	0.2	0.97	0.96
07/13/94	64	1.8	0.2	0.97	0.96
07/13/94	64a	6	0.4	0.99	0.97

92 percent over the duration of the test. The oxidation results for the AS and SE catalysts are comparable to those obtained during preliminary testing at the same test conditions.

The oxidation efficiency for the UA catalyst is somewhat less than that obtained during the preliminary test (approximately 98 percent) at the same test conditions. A fresh batch of catalyst was used for the extended test and it is possible that the physical properties of the second

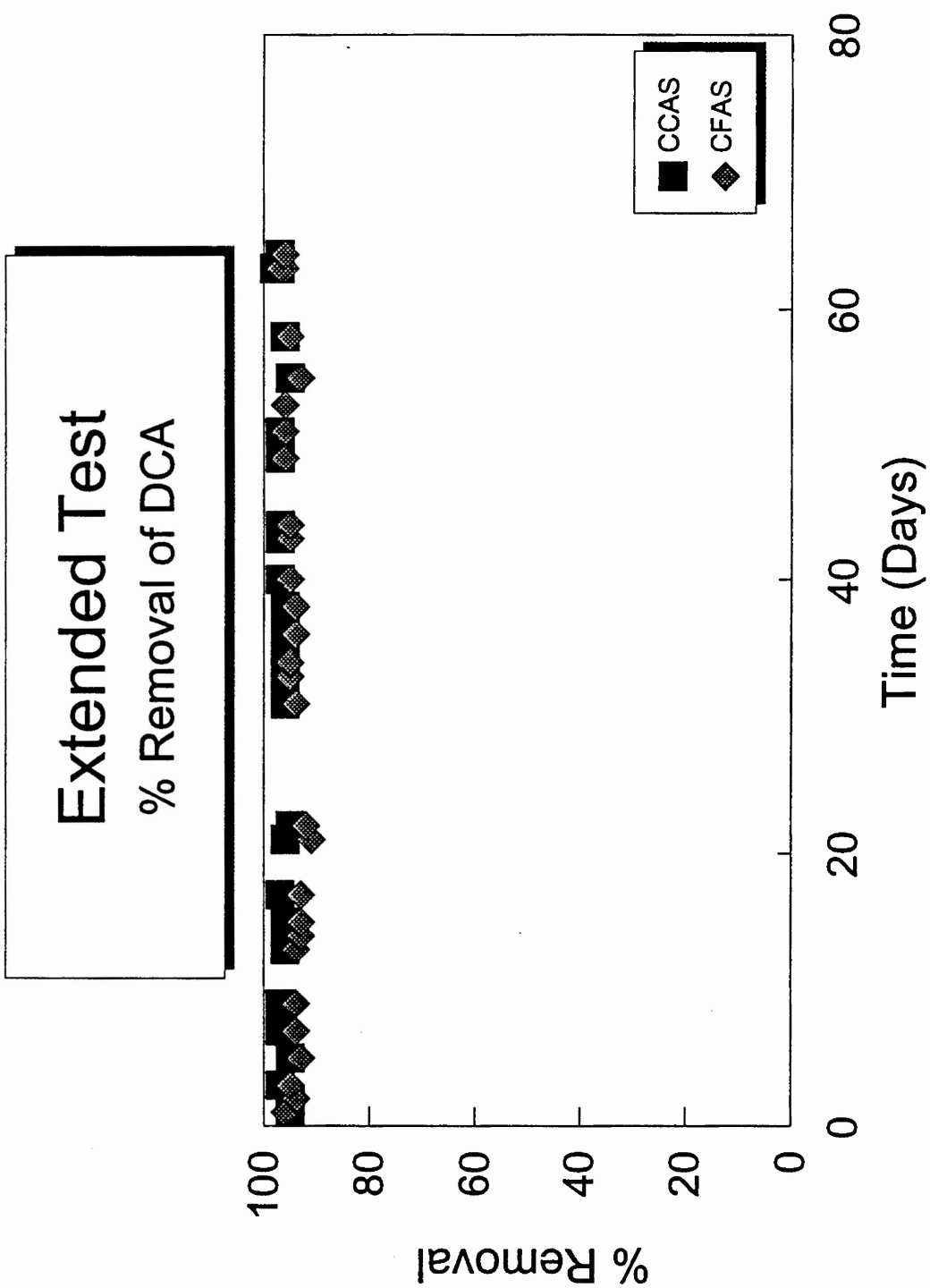


Figure 27. Comparison of the Stripping Efficiency of DCA during the Extended Test for the Crossflow and Countercurrent Towers.



# Extended Test Pressure-Drop Trends

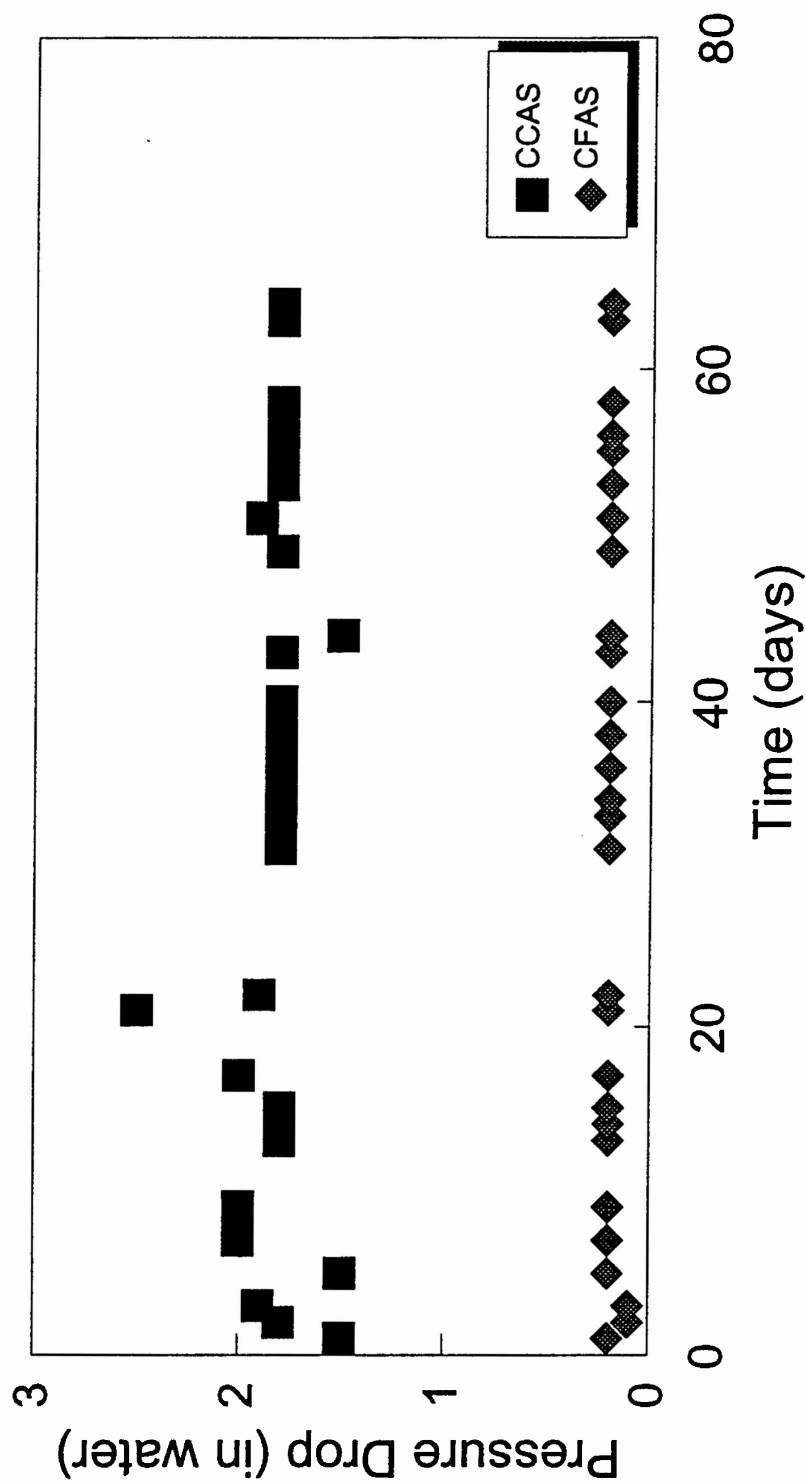


Figure 28. Pressure Drop Trends for the Crossflow and Countercurrent Towers during the Extended Test.

**TABLE 7. BENCH-SCALE CATALYTIC OXIDATION RESULTS**

Date	Day	% Destruction of DCA		
		UA	AS	SE
05/11/94	1	93.8	97.3	95.1
05/13/94	3	93.5	99.9	97.7
05/17/94	7	95.0	99.8	99.7
05/19/94	9	93.5	99.8	99.8
05/23/94	13	92.8	99.7	99.6
05/25/94	15	92.9	99.5	98.7
05/27/94	17	90.9	99.7	99.5
05/31/94	21	86.9	99.6	99.8
06/01/94	22	88.8	99.5	99.2
06/10/94	31	95.9	75.4	99.1
06/12/94	33	92.5	99.7	99.4
06/13/94	34	99.1	99.9	99.6
06/14/94	35	94.5	—	—
06/15/94	36	95.2	99.6	99.0
06/17/94	38	88.0	99.6	99.6
06/19/94	40	90.3	99.7	99.5
06/22/94	43	87.0	99.7	99.6
06/23/94	44	92.4	99.0	99.3
06/28/94	49	89.8	99.3	98.7
06/30/94	51	94.6	98.7	98.1
07/02/94	53	91.4	—	—
07/04/94	55	96.2	99.6	99.2
07/05/94	56	83.3	99.7	99.7
07/07/94	58	81.9	99.8	—
07/12/94	63	91.5	99.3	99.1

\*UA - University of Akron

AS - Allied Signal

SE - Salem Engelhard

batch may have been different from the first. Further testing of this catalyst may be required to confirm the high destruction obtained during the preliminary test.

Experimental catalyst X also was tested over a 10-week period. Conversion was extremely low. Space velocities and temperatures were varied to determine optimum operating conditions. The results of these tests are presented in Appendix F. Catalyst X can be considered to be still in an early developmental stage.

# Extended Test

## Catalytic Destruction of DCA

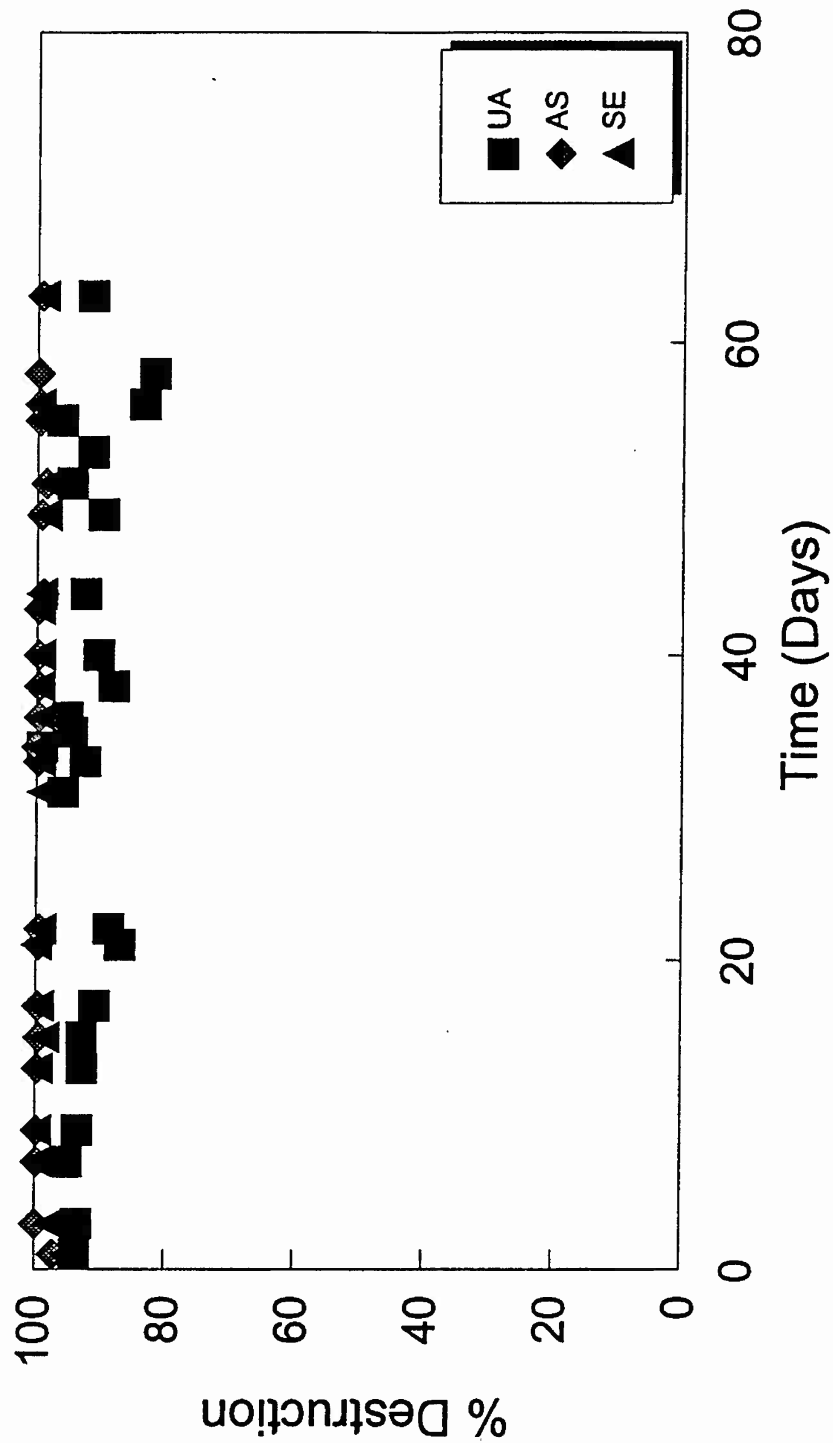


Figure 29. Catalytic Destruction of DCA for Three Fixed-Bed Catalysts.

**b. Pilot-Scale Photocatalytic Oxidizer**

Table 8 summarizes the results of the photocatalytic oxidation tests, which are graphed in Figure 30. Initially, 34 UV lamps were used in conjunction with an air preheater temperature of 180°F resulting in an average dichloroethane conversion of 95.6 percent, which was the design condition. During this phase of testing (34 UV lamps from 5/11/93 to 6/14/94), the oxidizer occasionally overheated and shut off. It was believed that the high ambient summer air temperature was interfering with the heating control mechanism of the oxidizer, causing the thermal overload

**TABLE 8. DCA DESTRUCTION USING A PILOT-SCALE PHOTOCATALYTIC OXIDIZER**

Date	Day	Number of Lamps	Air Flow Rate (scfm)	Inlet Temp (F)	Bed Temp (F)	% Conversion DCA
05/11/94	1	34	50	180	246	96.1
05/13/94	3	34	51	180	246	95.9
05/17/94	7	34	50	180	246	96.1
05/19/94	9	34	51	180	247	95.3
05/23/94	13	34	52	101	89	77.6
05/24/94	14	34	51	170	218	93.4
05/25/94	15	34	51	180	245	94.3
05/27/94	17	34	52	175	241	95.1
05/31/94	21	34	52	175	240	95.5
06/01/94	22	34	52	180	136	93.7
06/10/94	31	34	54	180	245	98.4
06/12/94	33	34	54	180	247	95.3
06/13/94	34	34	54	180	120	98.5
06/14/94	35	34	54	180	247	95.3
06/15/94	36	34	54	170	234	95.6
06/16/94	37	34	54	175	242	94.1
06/17/94	38	34	54	175	243	94.4
06/19/94	40	34	54	175	239	94.3
06/22/94	43	34	54	175	240	92.5
06/23/94	44	34	54	175	239	92.7
06/28/94	49	34	55	175	244	99.8
06/29/94	50	41	54	175	264	94.2
06/30/94	51	41	55	175	263	97.8
07/02/94	53	41	54	175	260	96.3
07/04/94	55	41	55	175	263	96.3
07/05/94	56	41	56	175	263	96.3
07/06/94	57	41	56	—	—	93.3
07/07/94	58	41	56	175	261	98.5
07/12/94	63	49	56	165	260	96.5
07/13/94	64	49	57	165	268	98.3

# Photocatalytic Oxidizer

## Oxidation of DCA

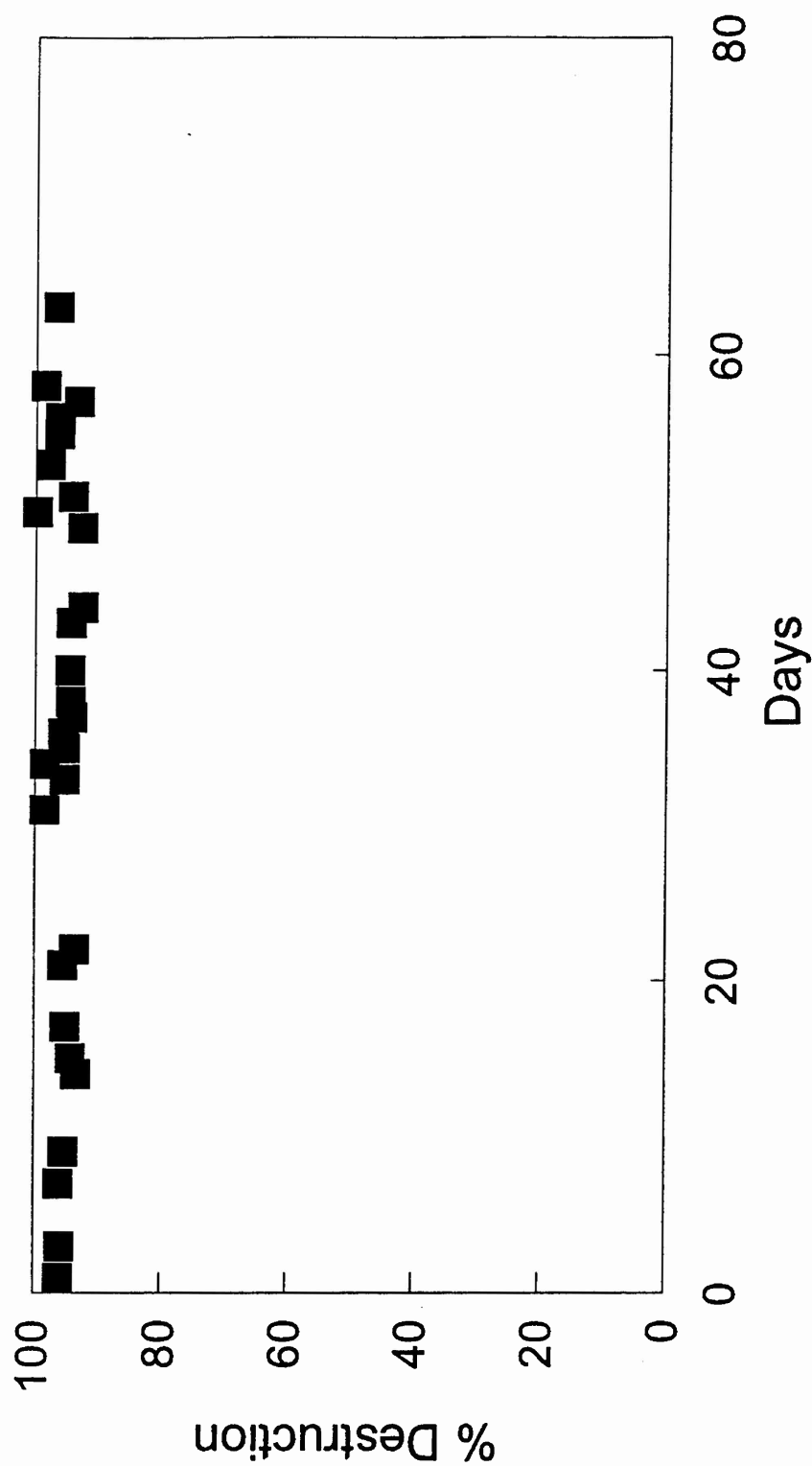


Figure 30. Catalytic Destruction of DCA Using a Pilot-Scale Photocatalytic Oxidizer.

switch to trip. To compensate, the preheater temperature was decreased to 175°F on very hot days. This resulted in slightly lower conversions. To increase the conversion, an additional row of seven lamps was activated. The average conversion during this phase of the test (41 lamps from 6/29/94 to 7/7/94) was 96.1 percent. Toward the end of the test period, the conversion was increased to 98.3 percent by activating another bank of lamps (another 8 lamps, for a total of 49).

### c. By-Product Analysis

An attempt was made during the preliminary and extended tests to analyze the airstream from the catalysts for by-products and products of incomplete oxidation. The results are summarized in Appendix G. However, several operational difficulties were encountered during this study, and further research may be necessary before any firm conclusions are drawn.

One main difficulty was the extremely low levels of organics present in the groundwater (approximately 1 ppm after spiking), which in turn resulted in very low levels of organics in the incoming airstream to the catalysts (approximately 2 to 3 ppmv). This made detection of by-products a challenge within the resources available for the study. Sensidyne™ detector tubes initially were used to estimate the presence of compounds such as carbon dioxide, carbon monoxide, and phosgene in the outlet air from the catalysts. Carbon dioxide was detected as expected. The detection limits of carbon monoxide (25 ppm) and phosgene (< 0.1 ppm) were too high in the detector tubes to provide meaningful results.

Selected air samples were collected in canisters and transported to an off-site laboratory for a comprehensive GC-MS analysis. Vinyl chloride was the only compound noticed at any significant level in the outlet air from all four catalysts (exceeding its concentration in the inlet air). This compound may be present as a product of incomplete oxidation. In any case, the levels of vinyl chloride (39 to 172 ppbv) in the outlet air are very low compared to the approximately 4,000 to 5,000 ppbv of chlorinated organics present in the inlet air to the catalysts. Therefore, the presence of vinyl chloride does not appear to be a major concern. Further research with higher contaminant loadings is needed to confirm these results.

Hydrogen chloride and chlorine were targeted for analysis in the airstreams from the catalysts. With the bench-scale catalysts, neither HCl (< 1 ppm) nor chlorine (< 0.5 ppm) was detected in the outlet air. First, the detection limits were relatively high. Second, the hot air leaving the catalysts was made to enter a stainless steel spiral tube to cool it down to a temperature where it could be sampled. Any HCl would be expected to deposit on this steel section.

Some HCl and chlorine were detected in the airstream leaving the pilot-scale photocatalytic unit, in which the air flow mass was higher than in the bench-scale catalysts. However, this pilot unit had a built-in line scrubber that was trapping most of the HCl produced. Therefore, a chlorine mass balance was not possible. Similar difficulties in obtaining chlorine detection and mass balance are reported by Hylton (1992) in his evaluation of catalytic oxidation at Wurtsmith AFB. Further research with higher contaminant loadings and without the use of a scrubber would be required to evaluate the by-products.

## SECTION VII DATA ANALYSIS

### A. MASS BALANCE

A mass balance was performed on the counterflow and crossflow towers for both the preliminary and extended tests using the following equation:

$$L_m(C_{L,in} - C_{L,out}) = G_m(C_{G,out} - C_{G,in}) \quad (3)$$

where  $C_{L,in}$  and  $C_{L,out}$  are the concentrations of the inlet and outlet water streams,  $C_{G,in}$  and  $C_{G,out}$  are the concentrations of the inlet and outlet airstreams, and  $L_m$  and  $G_m$  are the water and air mass flow rates. The percent difference between the left and the right sides of Equation (3) were calculated. The results are presented in Appendix H. The percent error in the mass balance was significantly less for the crossflow tower than the countercurrent tower for both the preliminary and extended tests. In general, the percent error for the extended test was greater than the error for the preliminary test, the average being 2.2 (crossflow tower) and 24.4 (countercurrent tower) for the preliminary test and 27.8 (crossflow tower) and 42.9 (countercurrent tower) for the extended test. The relatively large variation in the mass balance is attributed to the very low concentration of contaminant (DCA) encountered in this study. Because of this, small variations in concentration ( $C_L$ ,  $C_G$ ) and flow rate ( $L_m$ ,  $G_m$ ) measurements lead to large changes in mass estimates.

### B. MASS TRANSFER

The overall mass transfer coefficient ( $K_1a$ ) was calculated from the experimental data using the following design equations (Speece et al., 1987):

$$\text{Packed height, } Z = \text{HTU} \cdot \text{NTU} \quad (4)$$

where HTU = height of a transfer unit and NTU = number of transfer units.

$$\text{HTU} = \frac{L_m}{\rho_L K_1 a} \quad (5)$$

$$\text{NTU} = \left[ \frac{S}{S-1} \right] \text{Ln} \left[ \frac{(C_{L,in} - C_{G,in}/H)(S-1)}{(C_{L,out} - C_{G,out}/H)S} + \left[ \frac{1}{S} \right] \right] \quad (6)$$

where  $S$  is the stripping factor, defined as

$$S = \left[ \frac{H}{P} \right] \left[ \frac{G}{L} \right] \quad (7)$$

and  $Z$  is the packed height (meters),  $L_m$  is the water mass loading ( $\text{kg/m}^2/\text{s}$ ),  $\rho_L$  is the density of water ( $\text{kg/m}^3$ ),  $K_1a$  is the overall mass transfer coefficient ( $\text{s}^{-1}$ ),  $C_{L,in}$  is the DCA concentration in the inlet water ( $\text{kg/m}^3$ ),  $C_{G,in}$  is the DCA concentration in the inlet water ( $\text{kg/m}^3$ ),  $C_{L,out}$  is the DCA concentration in the outlet water ( $\text{kg/m}^3$ ),  $H$  is the Henry's Law constant (atm),  $P$  is the pressure of the air

(atm),  $G$  is the molar flow rate of the air (kmoles/s), and  $L$  is the molar flow rate of the water (kmoles/s). A value of 0.055 (dimensionless) was used for the Henry's Law constant (Ashworth et al., 1988). This value is in good agreement with Lamarche and Droste (1989) for DCA. Sample calculations of the overall mass transfer coefficient using Equations 4 through 7 and the experimental data are shown in Appendix I.

Figures 31, 32, and 33 present the experimental overall mass transfer coefficient as a function of the gas loading rate (constant liquid loading) for the CCAS tower. Figures 34, 35, and 36 present the same relationship for the CFAS tower. The mass transfer coefficient increases as the gas loading is increased, which is typical of compounds with low Henry's Law constants (Wood et al., 1990). This trend becomes more apparent as the water flow rate is increased. Figures 37, 38, 39, 40, 41, and 42 show the experimental overall mass transfer coefficient as a function of the liquid loading (at constant gas loading). The overall mass transfer coefficient is relatively independent of liquid loading in the range of water flow rates studied. This may indicate that the wetted area ( $a_w$ ) of the packing was still increasing sharply over the experimental range of flow rates (see Equation 9 on p. 66). Increasing  $L_m$  and increasing  $a_w$  (Equation 9) tend to cancel each other out. Generally,  $a_w$  approaches  $a_t$  asymptotically (Staudinger et al., 1990) at higher  $L_m$ . Therefore, at higher  $L_m$  values, the mass transfer coefficient is expected to increase with  $L_m$ .

Mass transfer coefficients for the CCAS and CFAS towers were estimated from three sources of data:

- Preliminary test data
- Extended test data
- The tower profile tests described in Section IV (subsection B.2).

The mass transfer coefficient values obtained at the experimental conditions of the preliminary and extended tests are listed in Appendix I and plotted in Figures 31 through 42. Except for a few outliers, the mass transfer coefficients for the CCAS tower obtained from the preliminary test conditions varied from approximately  $4 \times 10^{-3} \text{s}^{-1}$  to  $8 \times 10^{-3} \text{s}^{-1}$ . The variability is accounted for by the differences in air and water loadings (test conditions). Similarly, the CFAS tower mass transfer coefficients obtained from the preliminary test were in the range of approximately  $2 \times 10^{-3} \text{s}^{-1}$  to  $5 \times 10^{-3} \text{s}^{-1}$ .

The extended test was conducted at a single test condition (constant air and water loadings) and provides an average mass transfer coefficient for each tower. The average overall mass transfer coefficients ( $K_a$ ) over the 10-week extended test period were  $6.41 \times 10^{-3} \text{s}^{-1}$  and  $4.63 \times 10^{-3} \text{s}^{-1}$  for the CCAS and CFAS towers, respectively. These averages fall within the range of mass transfer coefficients obtained during the preliminary test.

The profile tests (Figures 20 and 21) in Section IV (subsection B.2) were conducted at selected test conditions. There was a good match between the mass transfer coefficients obtained for the same test conditions (water and air loadings) during the preliminary test and the coefficients obtained as the slope of the lines in Figures 20 and 21. For example, for Test 7r (20 gpm water flow and 250 scfm air flow), the mass transfer coefficients from the preliminary test were  $7.20 \times 10^{-3} \text{s}^{-1}$  and  $3.47 \times 10^{-3} \text{s}^{-1}$  in the CCAS and CFAS towers, respectively. For the same test conditions, the profile test indicated coefficients of  $6.97 \times 10^{-3} \text{s}^{-1}$  and  $3.39 \times 10^{-3} \text{s}^{-1}$  in the CCAS and CFAS towers, respectively. Thus, all three sources of mass transfer coefficients were in good agreement with each other.



# Overall Mass Transfer Coefficients

CC @ 20 GPM Water Flow Rate

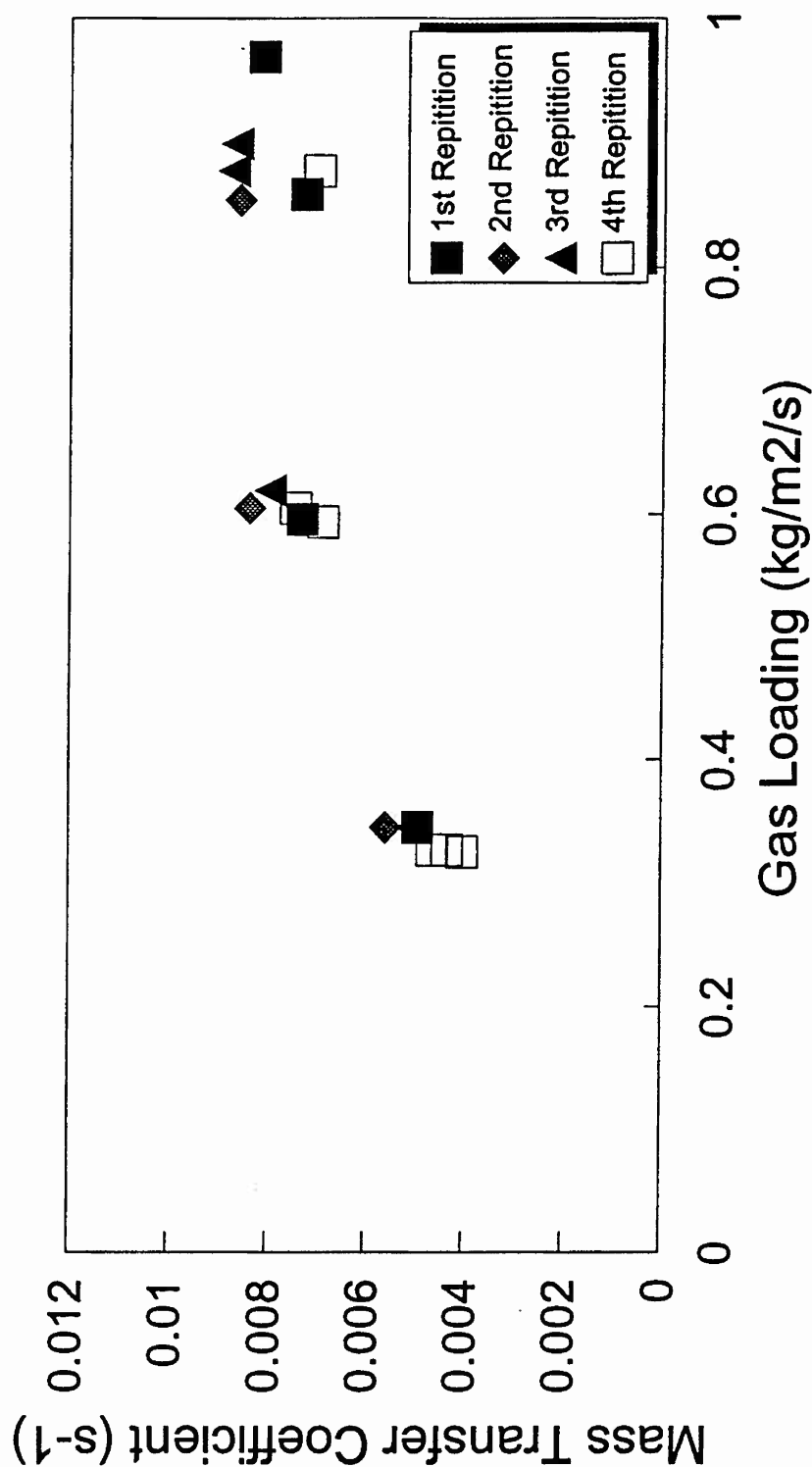


Figure 31. Dependence of the Mass Transfer Coefficient on Gas Loading at 20 gpm Water Flow Rate for the Countercurrent Tower.

# Overall Mass Transfer Coefficients

CC @ 35 GPM Water Flow Rate

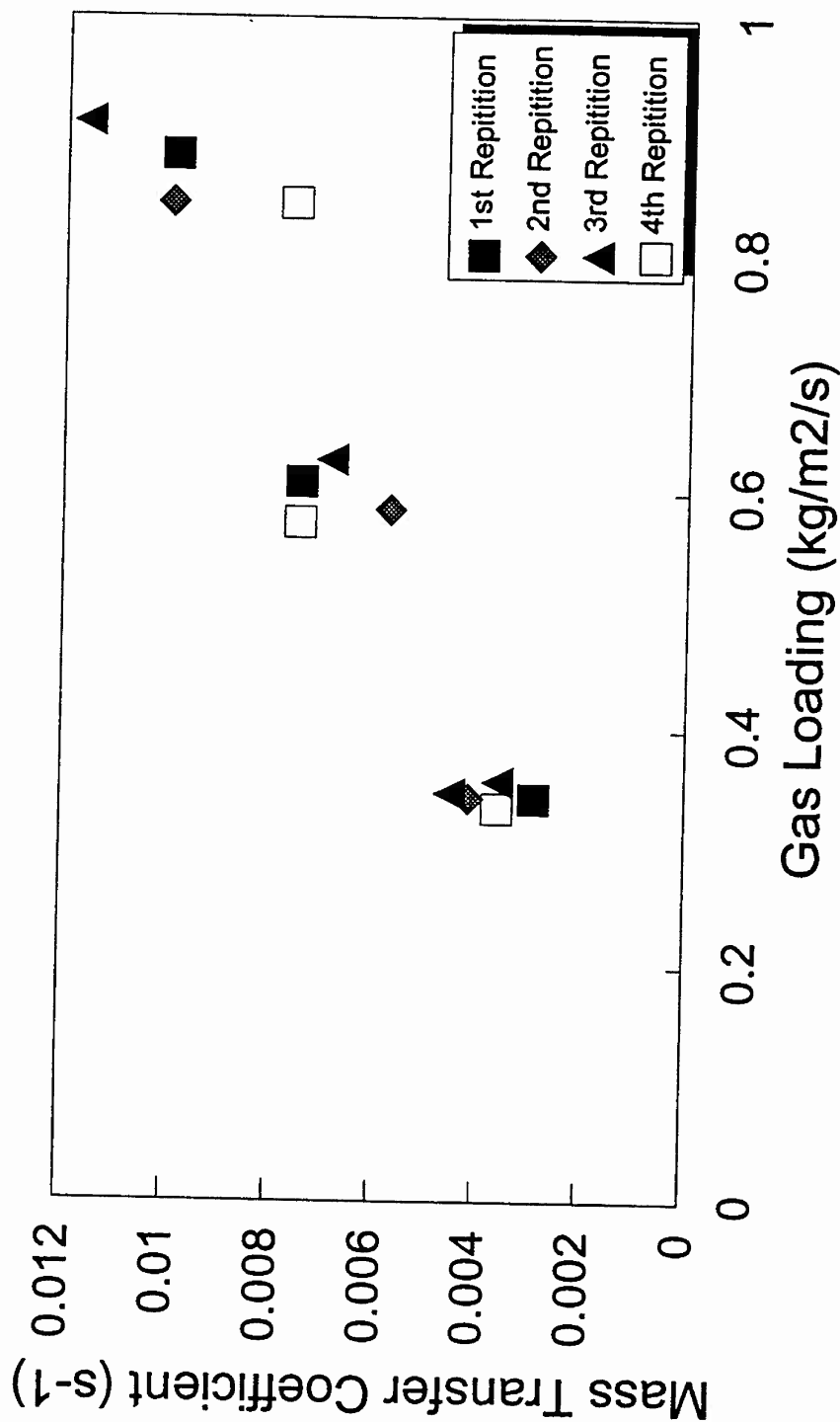


Figure 32. Dependence of the Mass Transfer Coefficient on Gas Loading at 35 gpm Water Flow Rate for the Countercurrent Tower.

# Overall Mass Transfer Coefficient CC @ 50 GPM Water Flow Rate

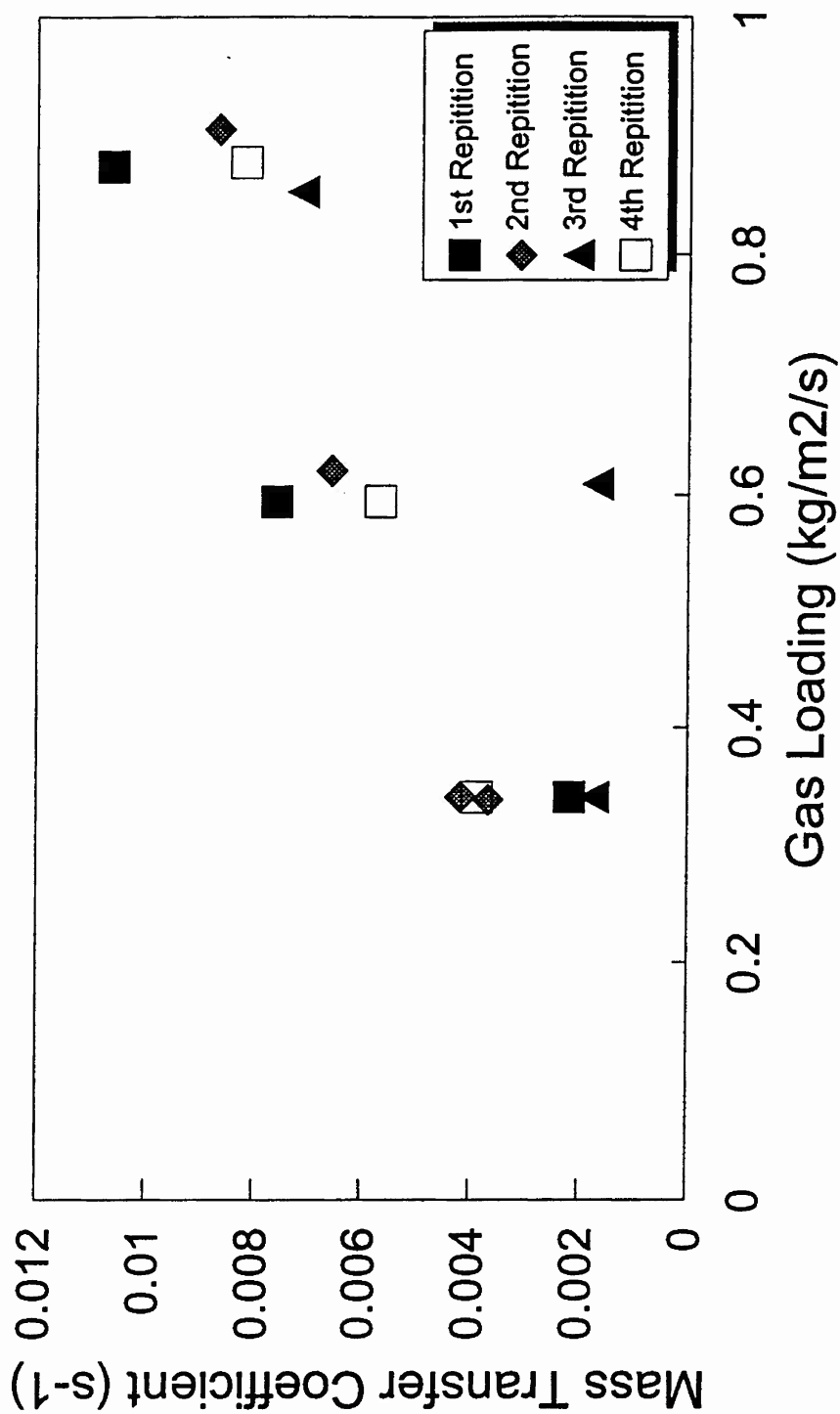


Figure 33. Dependence of the Mass Transfer Coefficient on Gas Loading at 50 gpm Water Flow Rate for the Countercurrent Tower.

# Overall Mass Transfer Coefficient

CF @ 20 GPM Water Flow Rate

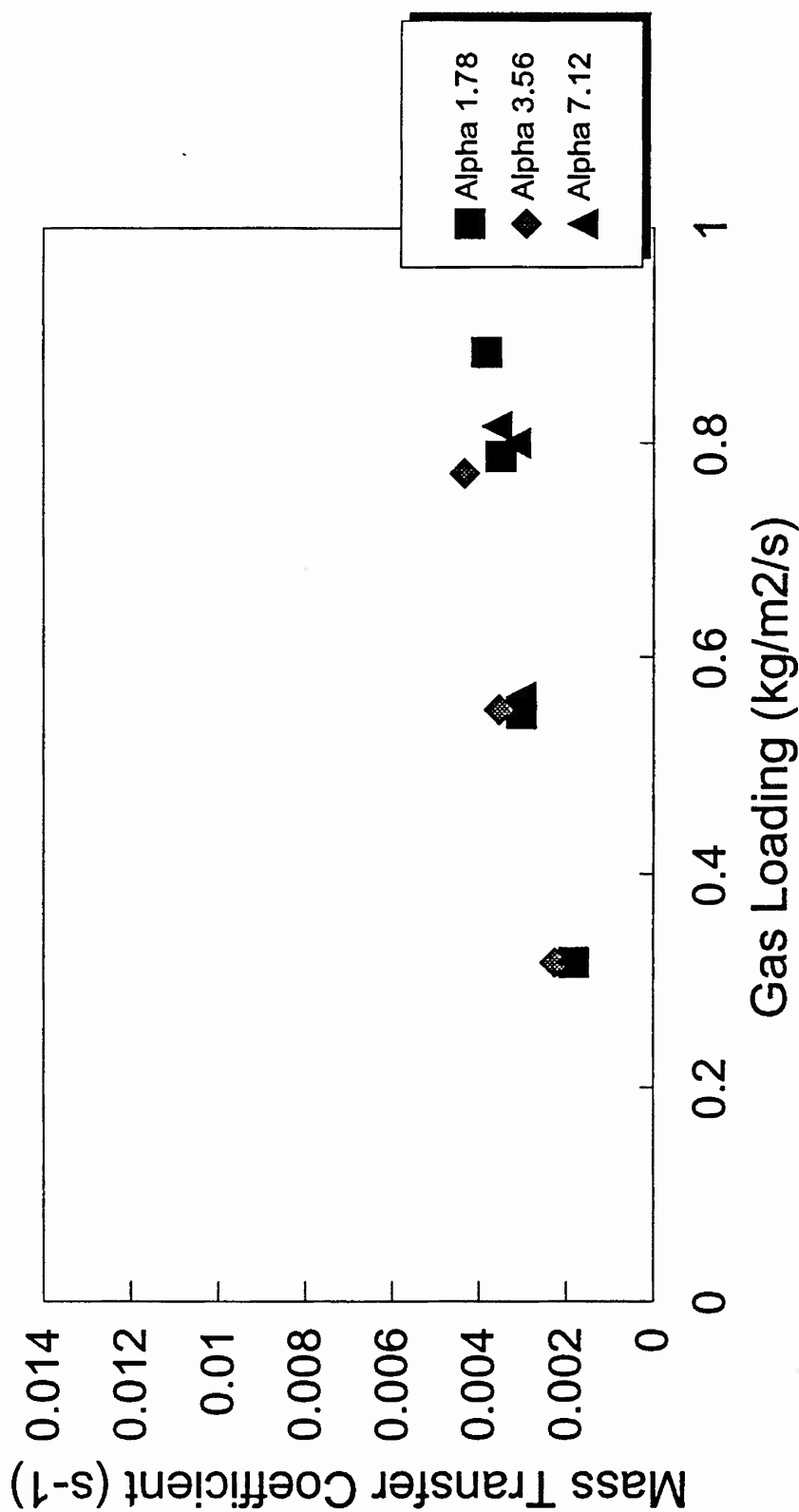


Figure 34. Dependence of the Mass Transfer Coefficient on Gas Loading at 20 gpm Water Flow Rate for the Crossflow Tower.

# Overall Mass Transfer Coefficients

CF @ 35 GPM Water Flow Rate

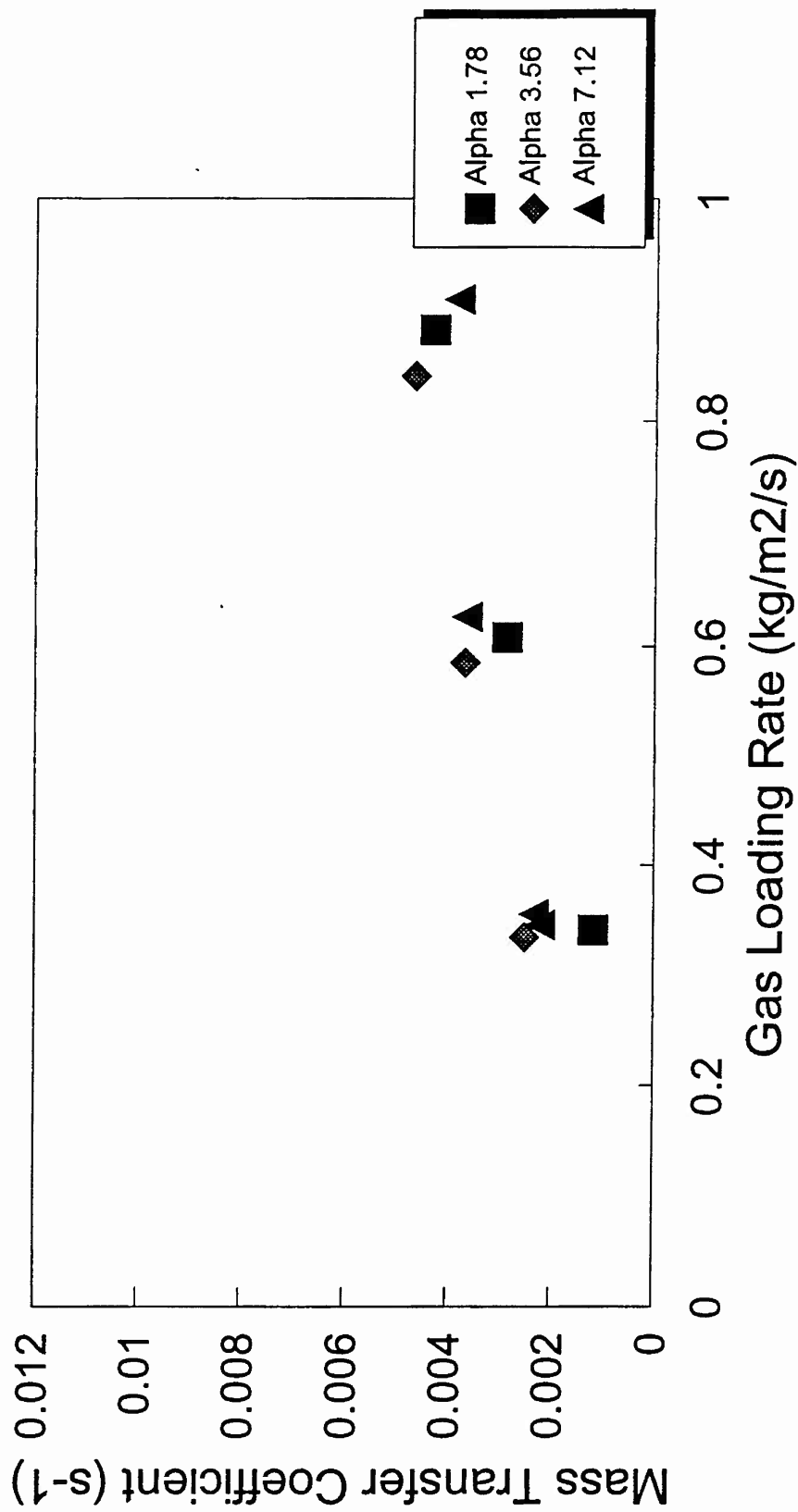


Figure 35. Dependence of the Mass Transfer Coefficient on Gas Loading Rate at 35 gpm Water Flow Rate for the Crossflow Tower.

# Overall Mass Transfer Coefficient

CF @ 50 GPM Water Flow Rate

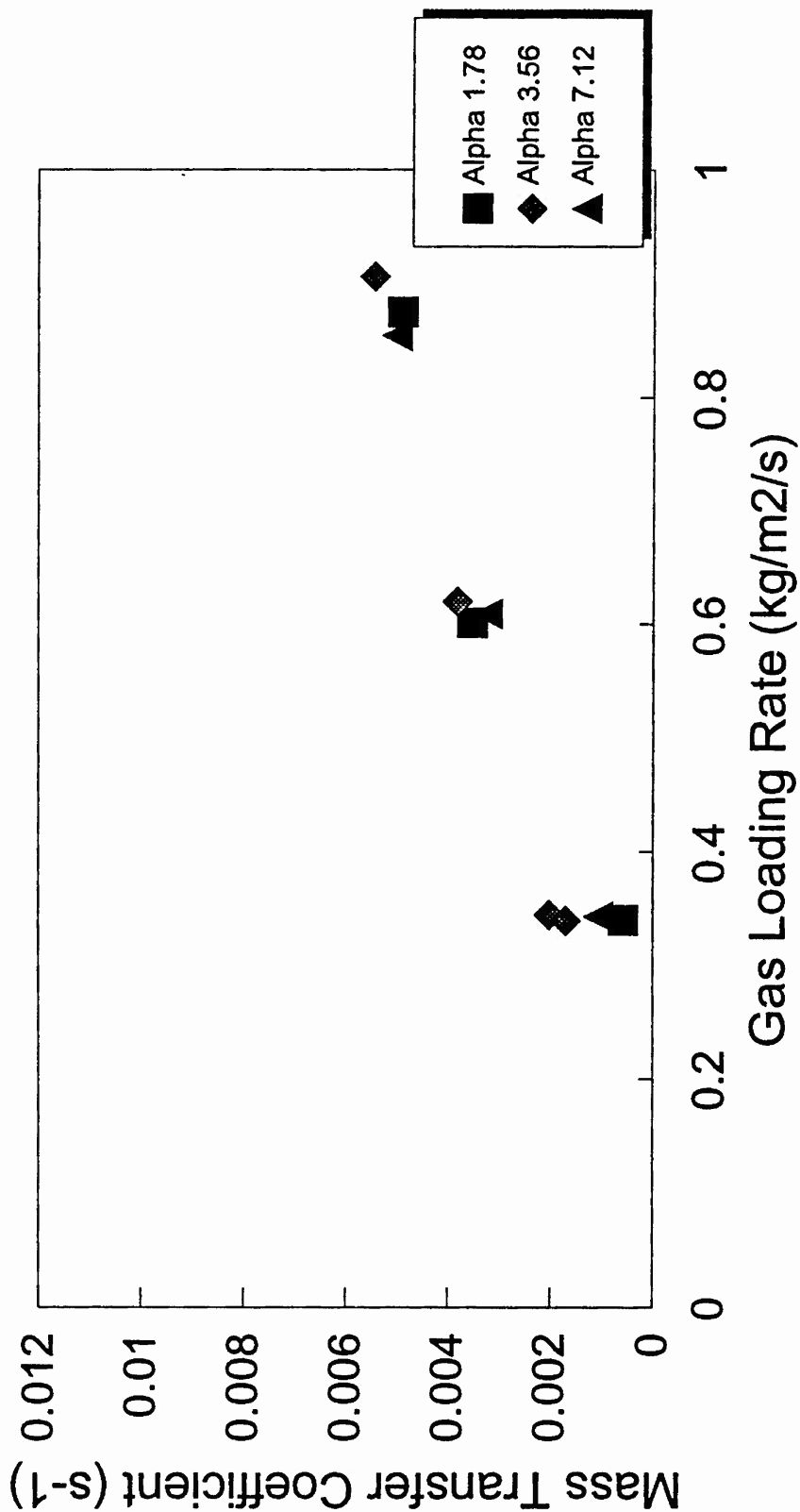


Figure 36. Dependence of the Mass Transfer Coefficient on Gas Loading at 50 gpm Water Flow Rate for the Crossflow Tower.

# Overall Mass Transfer Coefficients

CC @ 100 SCFM Air Flow Rate

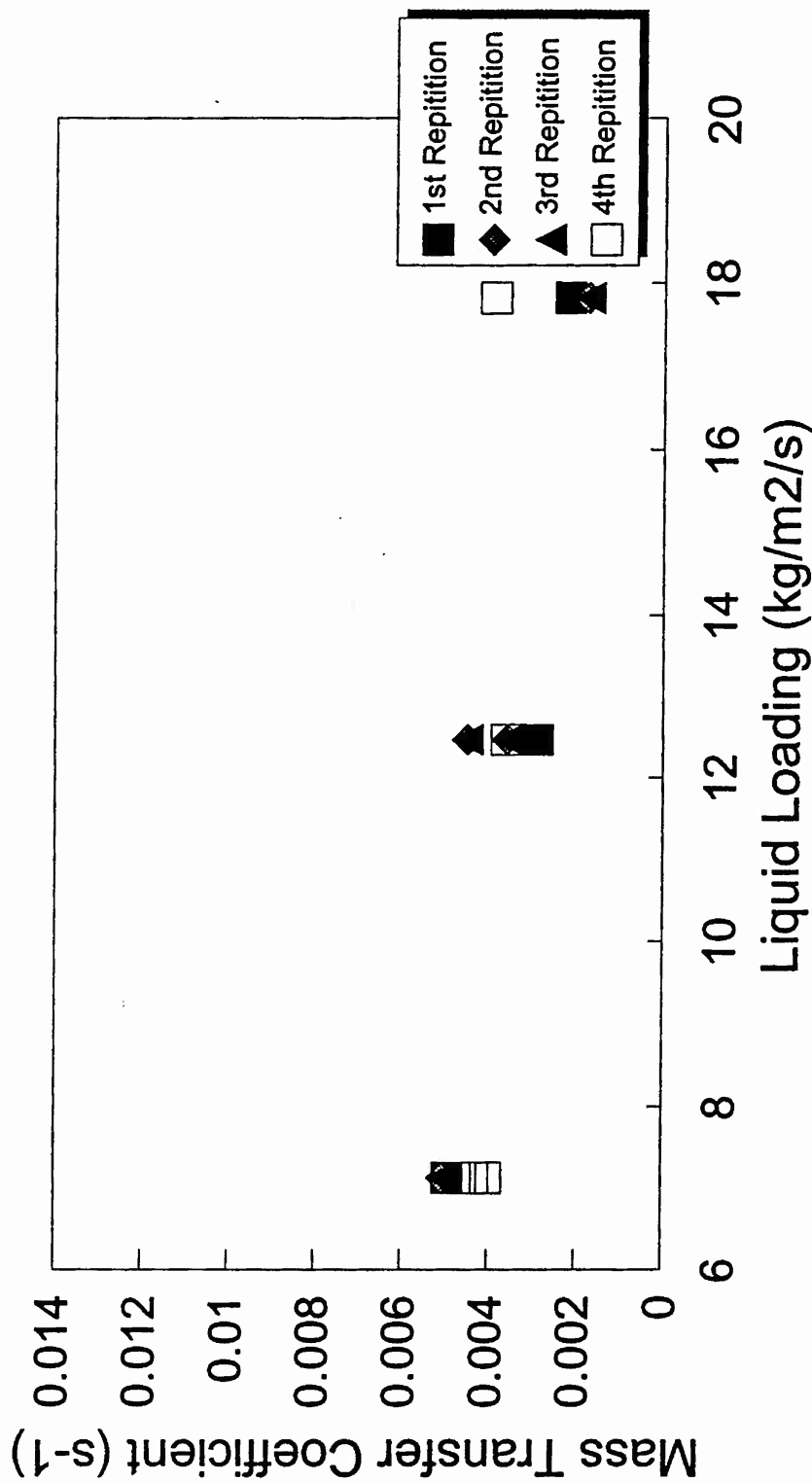


Figure 37. Dependence of the Mass Transfer Coefficient on Liquid Loading at a Gas Loading of 100 scfm for the Countercurrent Tower.

# Overall Mass Transfer Coefficients

CC @ 175 SCFM Air Flow Rate

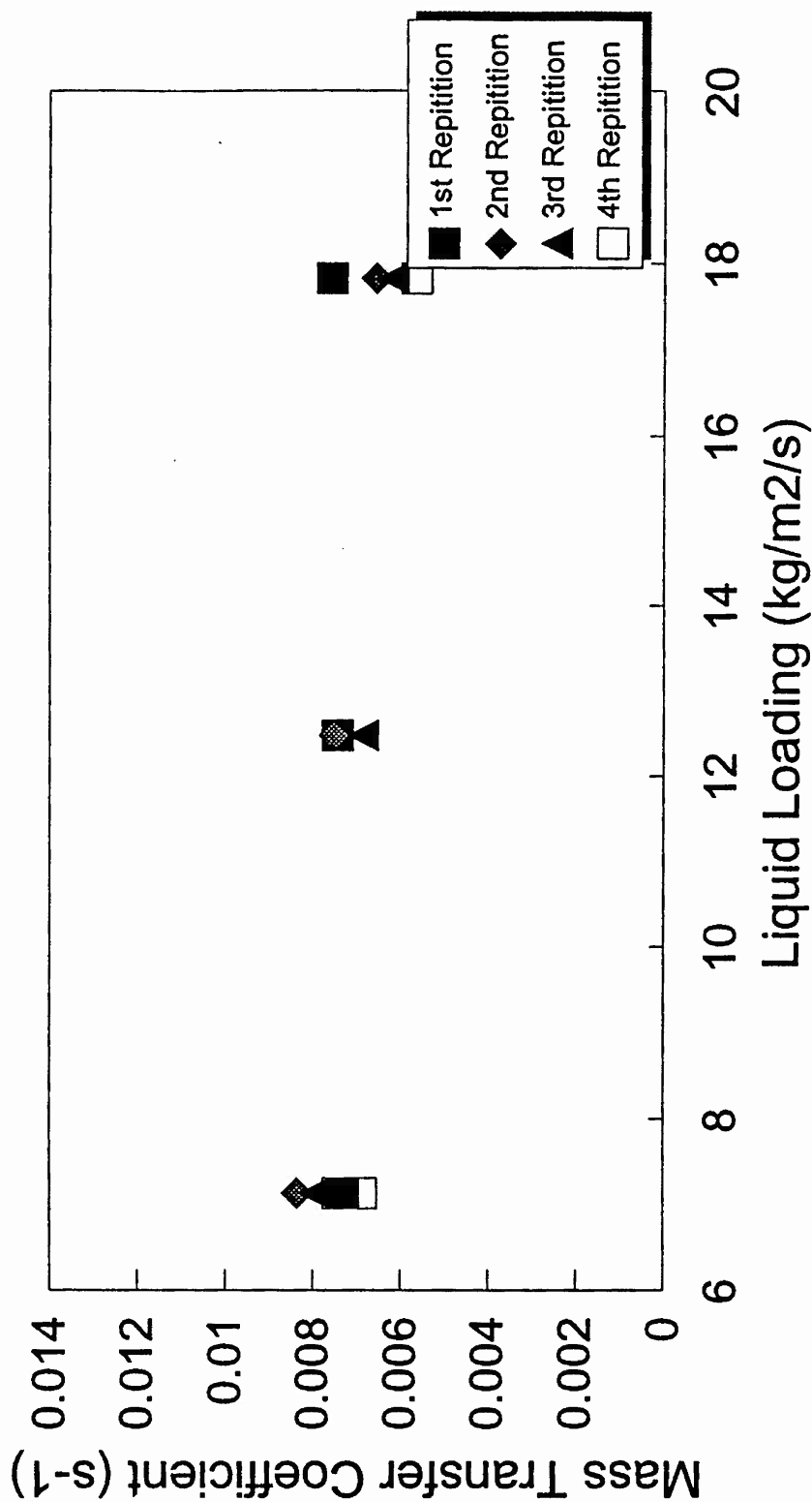


Figure 38. Dependence of the Mass Transfer Coefficient on Liquid Loading at a Gas Loading of 175 scfm for the Countercurrent Tower.



# Overall Mass Transfer Coefficients

CC @ 250 SCFM Air Flow Rate

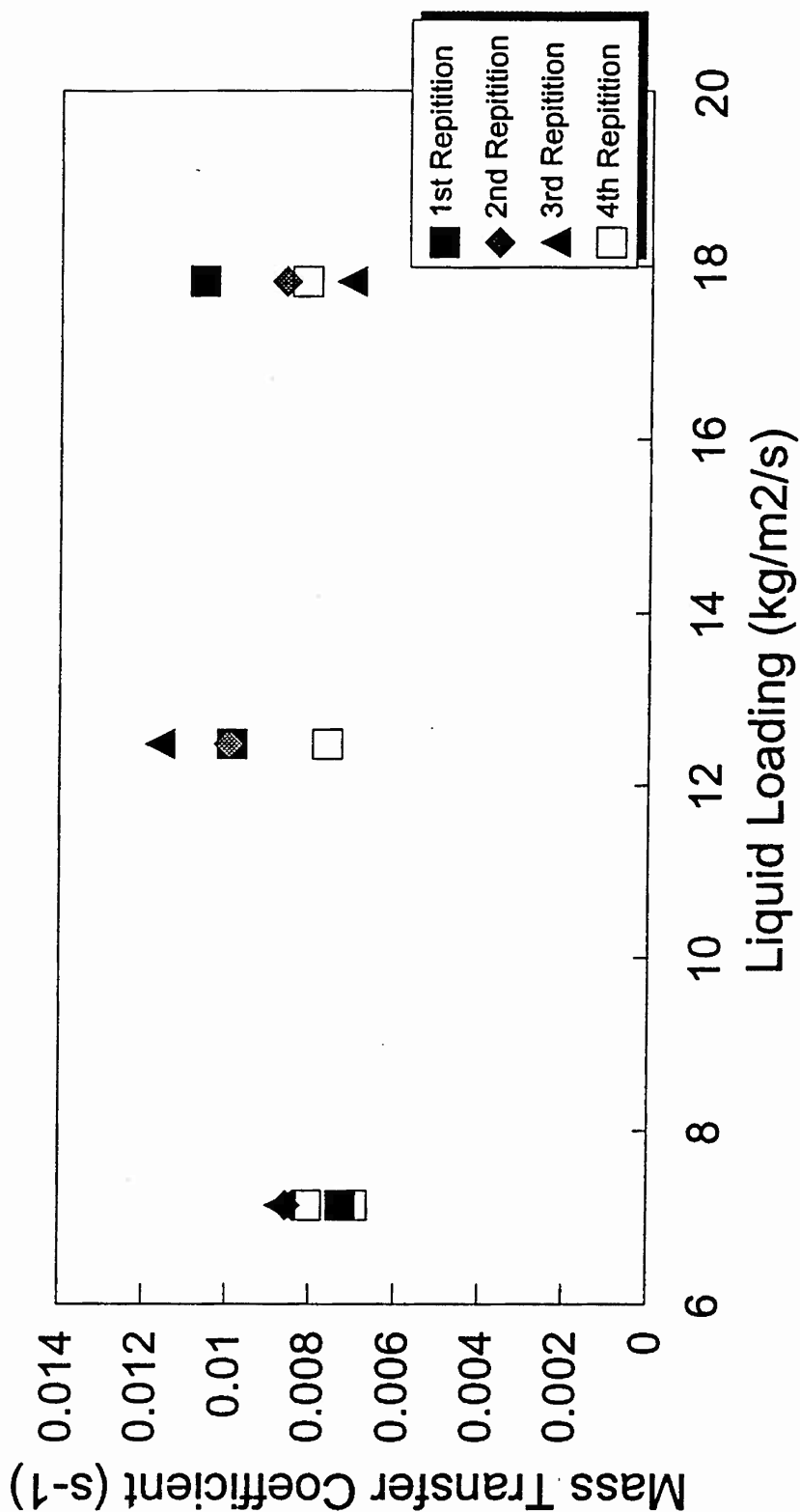


Figure 39. Dependence of the Mass Transfer Coefficient on Liquid Loading at a Gas Loading of 250 scfm for the Countercurrent Tower.

# Overall Mass Transfer Coefficients

CF Tower @ 100 SCFM Air Flow Rate

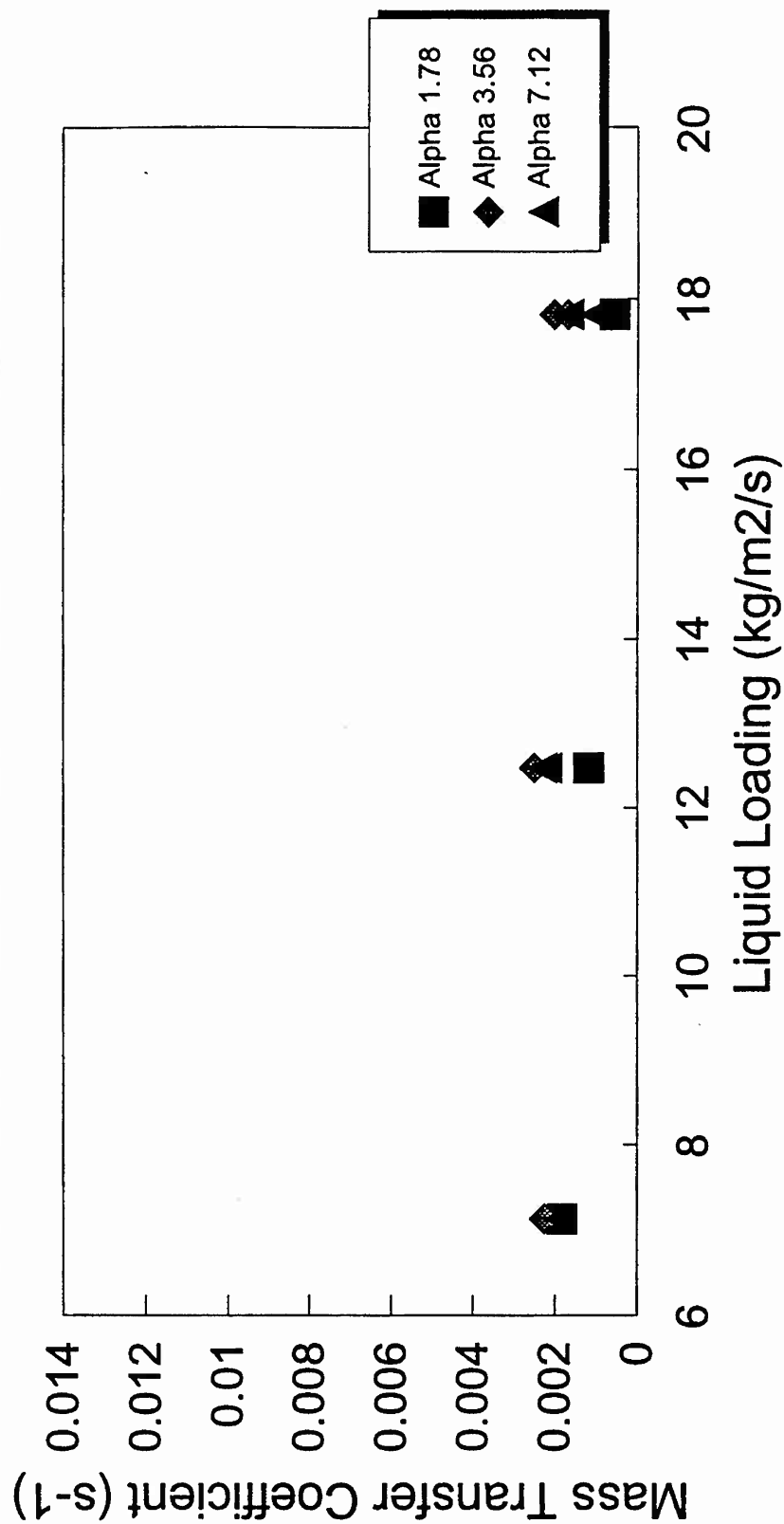


Figure 40. Dependence of the Mass Transfer Coefficient on Liquid Loading at a Gas Loading of 100 scfm for the Crossflow Tower.

# Overall Mass Transfer Coefficient

## CF Tower @ 175 SCFM Air Flow Rate

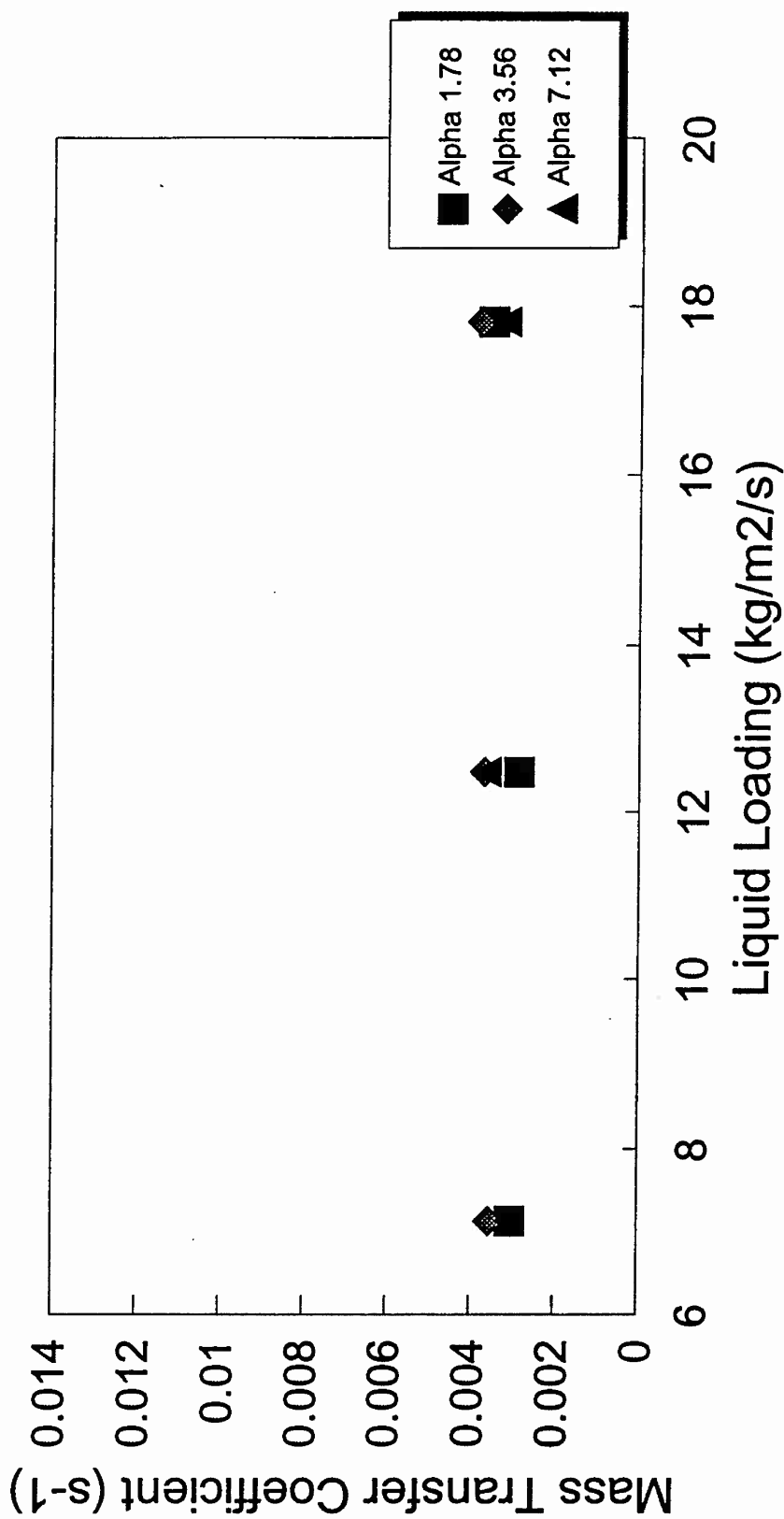


Figure 41. Dependence of the Mass Transfer Coefficient on Liquid Loading at a Gas Loading of 175 scfm for the Crossflow Tower.

## Overall Mass Transfer Coefficients

CF Tower @ 250 SCFM Air Flow Rate

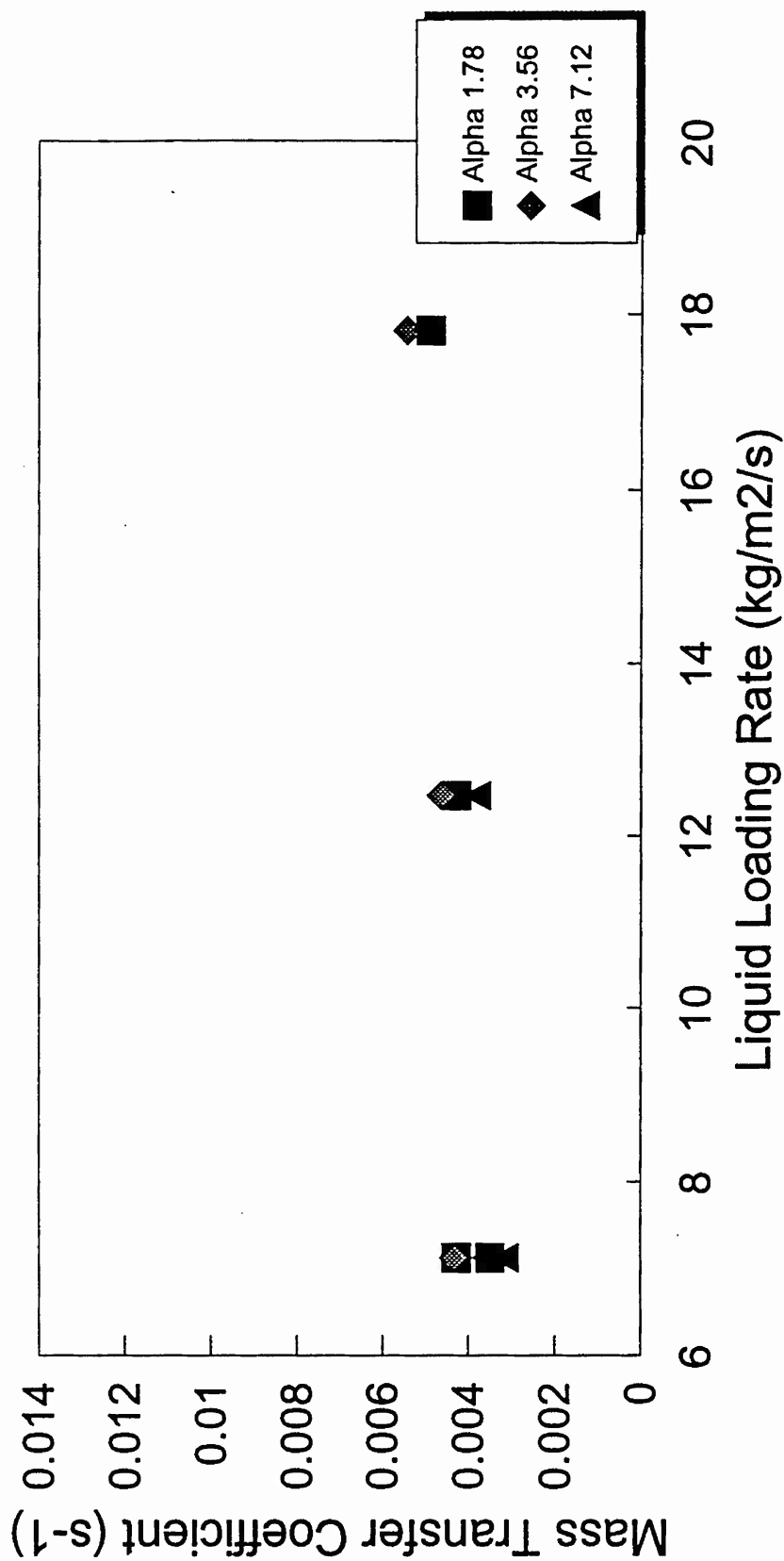


Figure 42. Dependence of the Mass Transfer Coefficient on Liquid Loading at a Gas Loading of 250 scfm for the Crossflow Tower.

The overall mass transfer coefficient,  $K_1a$ , is generally defined as

$$\frac{1}{K_1a} = \frac{1}{k_1a} + \frac{1}{Hk_ga} \quad (8)$$

where  $1/K_1$  is the liquid-phase resistance, and  $1/(H \cdot k_g)$  is the gas-phase resistance (Speece et al., 1987). A variety of theoretical correlations exist to calculate the individual liquid- and gas-phase resistances (Perry et al., 1984, and Staudinger et al., 1990). The most frequently used correlation is the Onda correlation (Wood et al., 1990). The Onda correlation is defined by the following three equations:

$$k_L \left[ \frac{\rho_l}{\mu_l g} \right]^{1/3} = 0.0051 \left[ \frac{L_m}{a_w \mu_l} \right]^{2/3} \left[ \frac{\mu_l}{\rho_l D_l} \right]^{-0.5} [a_t d_p]^{0.4} \quad (9)$$

$$\frac{k_g}{a_t D_g} = 5.23 \left[ \frac{G_m}{a_t \mu_g} \right]^{0.7} \left[ \frac{\mu_g}{\rho_g D_g} \right]^{1/3} [a_t d_p]^{-2} \quad (10)$$

$$\frac{a_w}{a_t} = 1 - \exp \left[ -1.45 \left( \frac{\sigma_c}{\sigma_l} \right)^{0.75} \left( \frac{L_m}{a_t \mu_l} \right)^{0.1} \left( \frac{L_m^2 a_t}{\rho_l^2 g} \right)^{-0.05} \left( \frac{L_m^2}{\rho_l \sigma_l a_t} \right)^{0.2} \right] \quad (11)$$

where  $g$  is the gravitational acceleration ( $m/s^2$ ),  $\rho_l$  and  $\rho_g$  are the liquid and gas densities ( $kg/m^3$ ),  $\mu_l$  and  $\mu_g$  are the liquid and gas viscosities ( $kg/m \cdot s$ ),  $a_w$  is the wetted interfacial area per unit volume ( $m^{-1}$ ),  $a_t$  is the total interfacial area per unit volume ( $m^{-1}$ ),  $D_l$  and  $D_g$  are the liquid and gas diffusivities ( $m^2/s$ ),  $d_p$  is the nominal packing diameter ( $m$ ), and  $\sigma_c$  and  $\sigma_l$  are the critical surface tension with respect to the packing material and the surface tension of the liquid ( $kg/s^2$ ). The individual resistances can be added to obtain the overall resistance ( $1/K_1$ ). The inverse of the individual mass transfer coefficients ( $k_l$  and  $k_g$ ) multiplied by the wetted interfacial area (" $a_w$ " or " $a$ ") yields the gas-phase resistances.

The individual gas-phase resistances and the overall mass transfer coefficient were calculated for the pilot data using the Onda equations. An average water temperature of approximately  $16^\circ C$  was used to estimate the physical properties of the water.  $G_m$  was computed using the inlet air temperature and assuming the air pressure to be equivalent to 1 atm. All other air properties were estimated for air at  $16^\circ C$ . This assumes that the air temperature instantly approaches the water temperature upon contact. The diffusivity of DCA in water was calculated using the Hayduk and Laudie method (Lyman et al., 1990), which is similar to the Wilke-Chang method. The diffusivity in air was calculated using the Fuller, Schettler, Giddings method (Lyman et al., 1990).

Generally, for volatile organics, the gas-phase resistance is expected to be much less than the liquid-phase resistance. Therefore,  $K_1a$  is generally assumed to be equivalent to  $k_1a$ . However, because of the relatively low Henry's Law constant associated with DCA, the gas-phase resistance is important. Therefore,  $1/k_1a$  cannot be assumed negligible. From the Onda equations, the gas-phase

resistance was calculated to contribute 4 to 18 percent of the overall resistance for both types of stripping towers. This result is in agreement with previous air-stripping studies (Wood et al., 1990).

Figures 43 and 44 plot the overall mass transfer coefficient calculated using the Onda equations against the experimental overall mass transfer coefficient. The experimental and Onda-predicted  $K_a$  were in fair agreement for the countercurrent tower, with points lying on both sides of the 45° line. The match was not as good with the crossflow tower. These figures show that the Onda correlation tends to overpredict the mass transfer coefficient in both the CCAS and CFAS towers. Usually, the Onda equations prove to be accurate correlations ( $\pm 25$  percent) when the mass transfer coefficient is liquid-phase controlled ( $1/(H \cdot k_g)$  is negligible). However, when there is a significant gas-phase resistance (as in our case), the Onda correlations have been observed to be only marginally acceptable (Munz, 1985). Table 9 compares the difference (error) between the experimental and theoretical overall mass transfer coefficients with the degree to which the mass transfer coefficient is gas-phase controlled. The larger the contribution of the gas phase to the overall resistance, the greater the deviation between experimental and Onda's  $K_a$ . The table shows that, as the percentage of gas-phase resistance decreases, the theoretical mass transfer coefficient approaches the experimental. This is in agreement with results from prior studies (Munz, 1985).

Prior studies (Wood et al., 1990) have shown that by modifying the equation for  $k_g$  (Equation 10), the accuracy of the theoretical overall mass transfer coefficient can be improved for the CFAS tower. The equation is modified by assuming that the air flows perpendicular to the water flow, through the vertical cross-sectional area between the baffles. Hence,  $G_m$  was divided by  $\alpha$  to obtain  $G_m^*$ . This improved the correlation by only a marginal amount. The average improvement for all of the pilot-scale tests was 3.5 percent.

Overall mass transfer calculations were also performed for another model that was proposed by Shulman (Shulman et al., 1955). It was found that the experimental overall mass transfer coefficients correlated less accurately using this correlation than they did with the Onda correlations.

# Comparison of Predicted and Experimental $K_{La}$

Countercurrent Tower

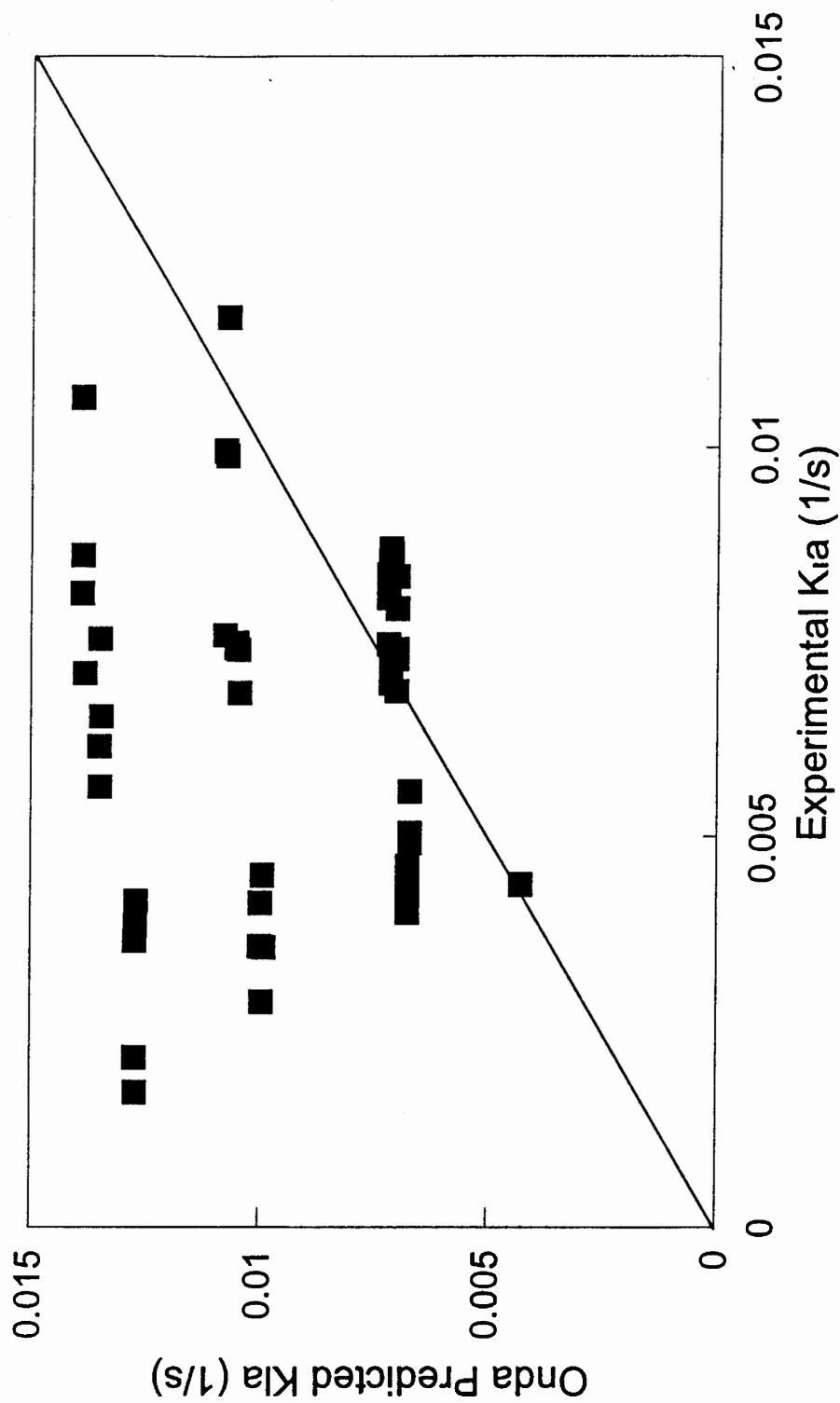


Figure 43. Comparison of the Overall Experimental Mass Transfer Coefficient to the Overall Mass Transfer Coefficient Calculated Using Onda's Equation for the Countercurrent Tower.

## Comparison of Theoretical and Experimental $K_{La}$

Crossflow Tower

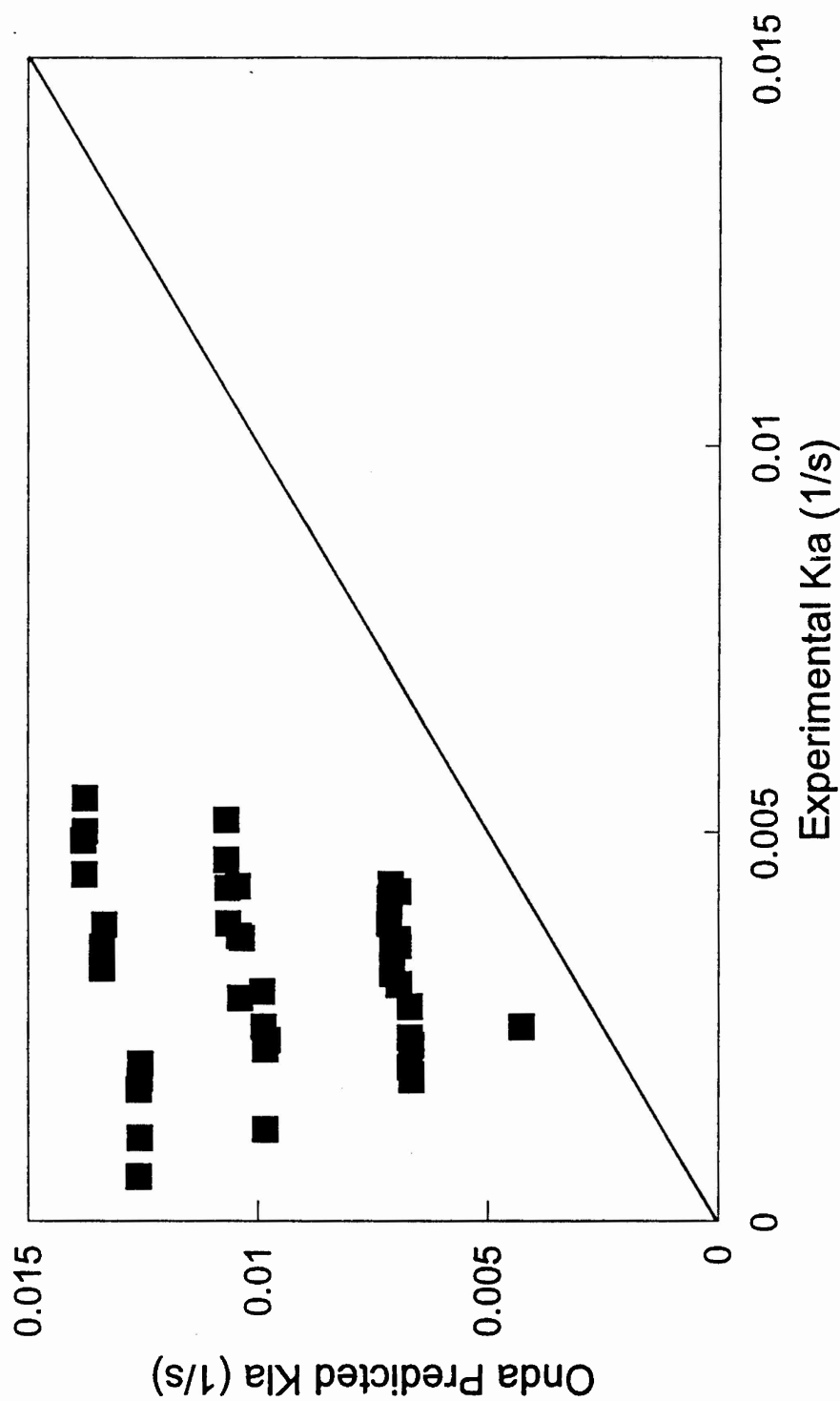


Figure 44. Comparison of the Overall Experimental Mass Transfer Coefficient to the Overall Mass Transfer Coefficient Calculated Using Onda's Equation for the Crossflow Tower.



**TABLE 9. EFFECT OF GAS-PHASE RESISTANCE ON THE PERCENT ERROR BETWEEN EXPERIMENTAL AND ONDA-PREDICTED OVERALL MASS TRANSFER COEFFICIENTS**

Test	% Error Between Experimental $K_L a$ and Onda $K_L a$		% of Overall resistance which is gas phase resistance	
	CC	CF	CC	CF
1	60.3	75.3	12.7	12.9
2	42.5	70.2	11.9	12.2
2	33.7	58.3	12.0	12.2
2	38.0	64.4	12.0	12.2
3	32.9	51.5	8.6	8.7
4	65.3	69.8	15.3	15.5
5	45.1	67.6	10.0	10.4
6	0.3	48.2	8.7	8.9
6	7.1	39.2	8.7	8.9
7	8.3	50.8	6.9	7.1
8	31.6	58.1	10.6	10.8
9	70.8	85.4	17.9	18.1
E1	-9.5	42.3	6.2	6.4
E2	2.3	43.4	6.2	6.4
10	54.6	71.6	12.9	13.1
11	21.4	66.2	12.6	12.8
12	12.2	56.4	8.5	8.7
13	59.8	74.5	15.4	15.6
14	42.4	60.7	10.1	10.4
15	-12.5	49.3	8.8	8.9
16	-12.8	39.3	6.7	6.8
17	31.6	64.6	10.8	11.0
18	68.8	83.9	18.0	18.3
18	72.3	86.5	17.8	18.0
19	57.1	75.8	12.6	12.9
20	29.4	71.9	12.6	12.8
21	-0.3	64.5	8.9	9.1
22	66.3	76.6	16.1	16.4
22	57.1	77.7	15.7	16.0
23	52.4	63.9	10.4	10.5
24	-6.3	56.7	8.9	9.0
25	-14.3	55.7	6.9	7.1
25	-11.9	49.9	7.0	7.2
26	39.1	65.4	11.3	11.7
27	73.8	84.6	17.9	18.1
1r	46.9	73.6	12.6	12.8
2r	30.9	72.9	12.6	12.7
3r	13.8	60.2	8.8	9.0
4r	72.5	88.1	15.7	15.9
5r	28.3	64.7	10.0	10.2
6r	1.6	56.6	8.7	8.9
7r	4.4	51.1	7.0	7.1
8r	33.4	72.7	11.1	11.3
9r	83.8	95.5	17.8	18.0
X1	-6.2	46.7	6.1	6.3
X2	44.9	41.9	4.4	4.5

## SECTION VIII SCALEUP

### A. AIR STRIPPING TOWERS

The data collected during the preliminary and extended test can be used to design larger air-stripping countercurrent and crossflow towers for full-scale remediation of a site. This section describes the methodology used to scale-up the towers to handle a 180-gpm water flow rate. The same methodology can be used to design towers for handling a variety of site conditions.

The design basis is determined by the remediation site. At the outset, the following parameters need to be determined and fixed for a given site:

- Type of contaminant: This fixes the Henry's Law constant.
- Water flow rate: This is determined based on the estimated volume of water to be treated at the site, the period of operation, and the treatment system characteristics.
- Contaminant concentrations and regulatory cleanup level: This determines the stripping efficiency required in the towers. Alternatively, the stripping efficiency can be independently fixed at 95 or 99 percent based on economic considerations (discussed in Section IX).

Appendix J shows the spreadsheet used for scaling up. Assuming that the Dover site were to be remediated at a rate of 250,000 gpd, a treatment plant that treats approximately 180 gpm has to be designed. The contaminant is DCA at a level of 1,000 ppb (1 ppm). Assuming that the cleanup level is 50 ppb gives a stripping efficiency requirement of 95 percent removal. Figures 17 and 18 show the air-to-water ratio that will give us 95 percent removal in the CCAS and CFAS towers. Also, based on our extended test experience we know that air-to-water ratios of 60 and 94 in the CCAS and CFAS towers, respectively, provide approximately 95% removal of DCA. Based on 180 gpm of water and the above air-to-water ratios, we need approximately 1,440 scfm and 2,250 scfm of air flow for the CCAS and CFAS towers, respectively.

We now need to determine the *liquid mass loading*. During the extended test, we were able to use a liquid loading of around 11 gpm/ft<sup>2</sup> (based on 20 gpm through the 18-inch and 24-inch diameter towers) in both CCAS and CFAS towers. In the scale-up, we could either retain the same liquid loading in both towers or adjust the liquid loadings slightly in both towers to obtain the same tower heights (to make the economic comparison easier). Thus, we assumed a liquid loading of 13.0 gpm/ft<sup>2</sup> in the CCAS tower and a liquid loading of 10.5 gpm/ft<sup>2</sup> in the CFAS tower. Some amount of iteration may be necessary to arrive at these values.

Now we are in a position to determine the *diameter* of the tower. Based on the 180-gpm water flow rate and the liquid loadings mentioned above, the packed horizontal cross-sectional areas required for the CCAS and CFAS towers are 13.8 square feet and 17.1 square feet, respectively. These packed areas correspond to a diameter of 4.2 feet for the CCAS tower and a diameter of 6.0 feet for the CFAS tower. Note that the 6.0-foot diameter of the CFAS tower corresponds to a packed horizontal cross-sectional area that is only 60.7 percent of the total horizontal cross-sectional area, because there is no packing in the baffled portion.

At this point, we need to examine the *pressure drops* that may be expected in the two towers and ensure that the liquid and air loadings selected do not cause flooding. Figures 45 and 46 summarize the pressure drops obtained during the preliminary test. If we continue to use 1-inch Pall rings in the scaled-up towers, we can expect a pressure drop of approximately 0.12 inch of water per foot of packing in the CCAS tower. This is also in agreement with the 2-inch pressure drop observed in the 17-foot packed height of the CCAS tower during the extended test. For the CFAS tower we expect an order-of-magnitude lower pressure drop.

Alternatively, pressure drops could be verified using the Eckert plots of the types shown in Figures 6 and 7. These plots are available from the packing manufacturers for conventional CCAS towers for different types and sizes of packing. For the CFAS tower, the pressure drop would have to be estimated, although an order of magnitude lower than the CCAS tower seem like a good rule of thumb estimate.

Next, the *overall mass transfer coefficient* value is determined. Figures 47 and 48 summarize the variability of the overall mass transfer coefficient with liquid and gas loadings for the CCAS and CFAS towers, as determined during the preliminary test. Based on the 13.0-gpm/ft<sup>2</sup> liquid loading and 104-scfm/ft<sup>2</sup> air loading for the CCAS tower, a  $K_{\text{a}}$  value of 0.00641 s<sup>-1</sup> can be used. This value also corresponds to the average  $K_{\text{a}}$  calculated during the extended test during similar conditions. For the CFAS tower, a  $K_{\text{a}}$  value of 0.00463 s<sup>-1</sup> is obtained for 10.5-gpm/ft<sup>2</sup> liquid loading and 132-scfm/ft<sup>2</sup> air loading. Again, this  $K_{\text{a}}$  value corresponds to the average  $K_{\text{a}}$  noted during the extended test in the CFAS tower.

Now we can use Equations (4) through (7) in Section VII to determine the *height* of the towers. The height of both towers works out to be approximately 17 feet. Note that we arrived at the same height for both towers through a process of iteration by adjusting the liquid and air flow rates in the two towers. This was done to enable a direct economic comparison of the two towers. The same stripping efficiency could be achieved by using a different combination of height and diameter in either tower.

Figure 49 shows the variation of tower *diameter* with liquid loading, everything else remaining the same. By using higher liquid loadings the diameter of the tower can be reduced. But, a larger height will be required to obtain the same stripping efficiency. Also, the lower the diameter, the higher is the liquid loading, and the higher is the pressure drop associated with the tower (see Figures 45 and 46).

Figure 50 shows the variation of tower *height* with stripping efficiency, everything else remaining the same. The higher the stripping efficiency required, the greater the height. The height of the tower also increases as the stripping efficiency required increases. In general, appropriate diameters and heights should be selected through an iterative process.

For conventional CCAS towers, often it is most economical to work towards standard sizes of towers offered by manufacturers. For the crossflow tower, we have the advantage of being able to go to higher air-to-water ratios without flooding the tower. Actual flooding conditions could not be determined for the CFAS tower during the pilot test because of the limitations of the blower. However, previous studies by Mertoetomo et al. (1993) with an 8-ft-tall CFAS tower have reported achieving air-to-water ratios of 350 without noticing any flooding.

# Effect of Air to Water Ratio on Pressure Drop

CCAS Tower

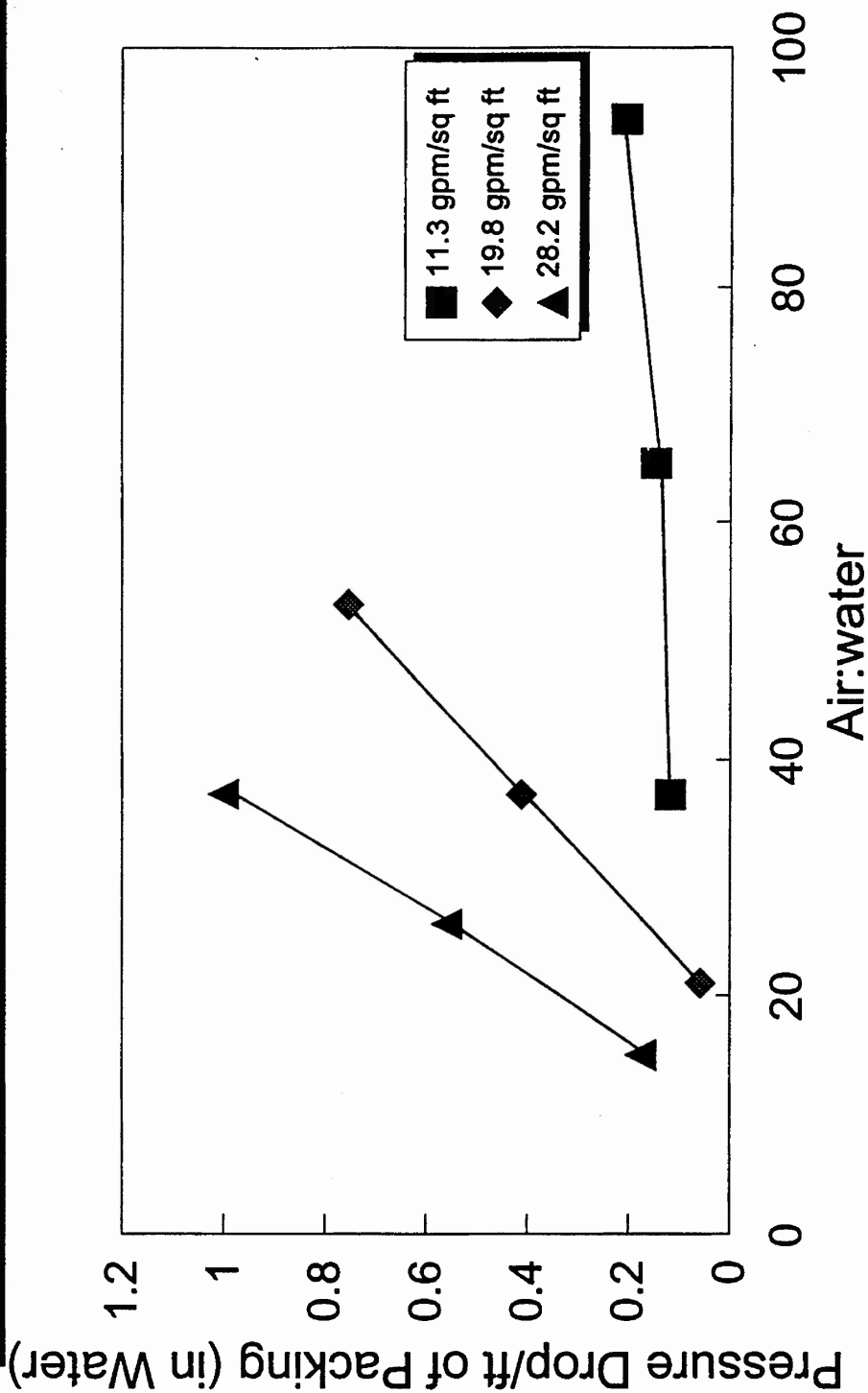


Figure 45. Effect of Air-to-Water Ratio on Pressure Drop in the CCAS Tower.

# Effect of Air to Water Ratio on Pressure Drop

Crossflow Tower

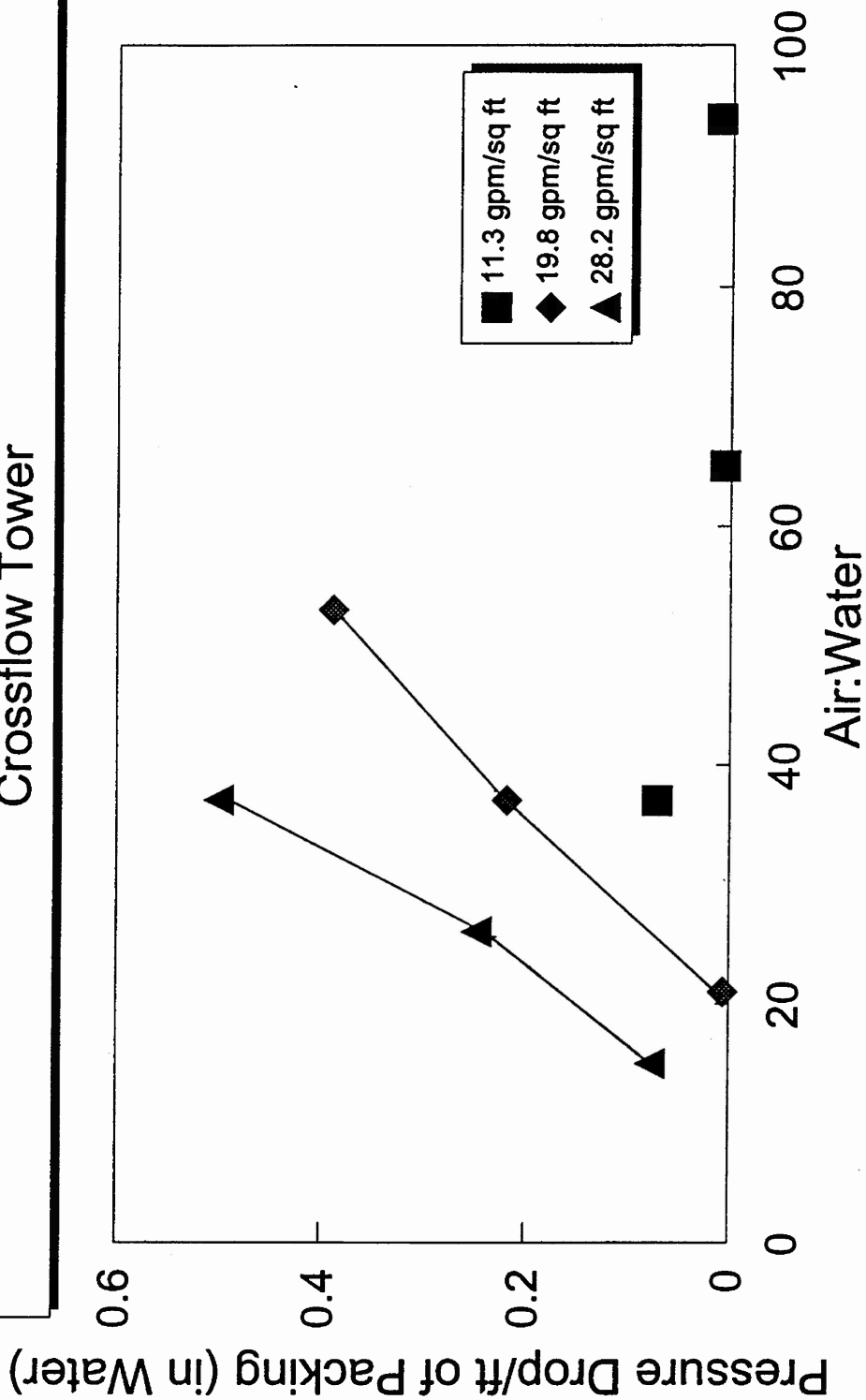


Figure 46. Effect of Air-to-Water Ratio on Pressure Drop in the CFAS Tower.

# Nomograph for Mass Transfer Coefficients

CCAS Tower

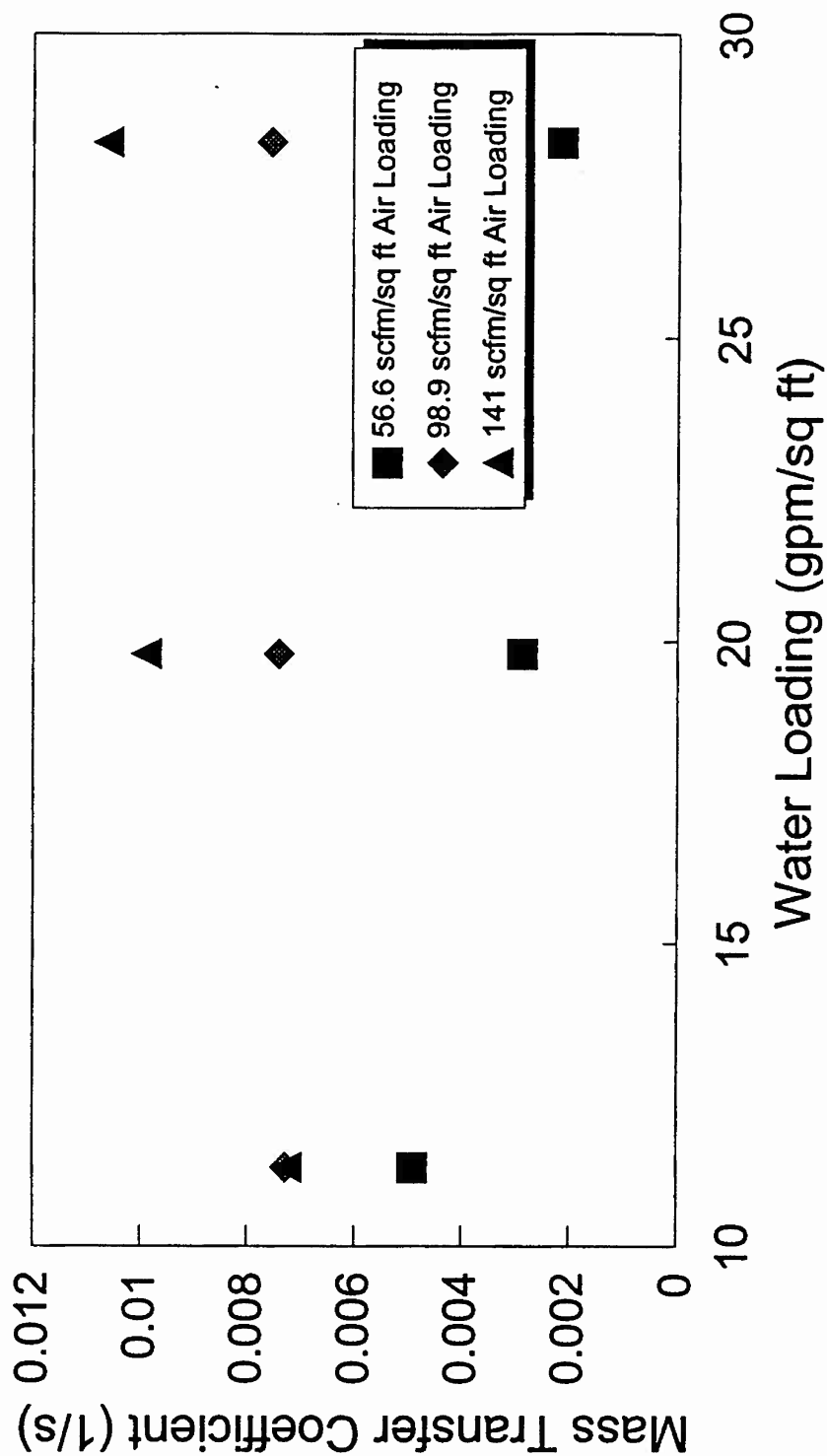


Figure 47. Mass Transfer Coefficients for the CCAS Tower.

# Nomograph for Mass Transfer Coefficients

## CFAS Tower

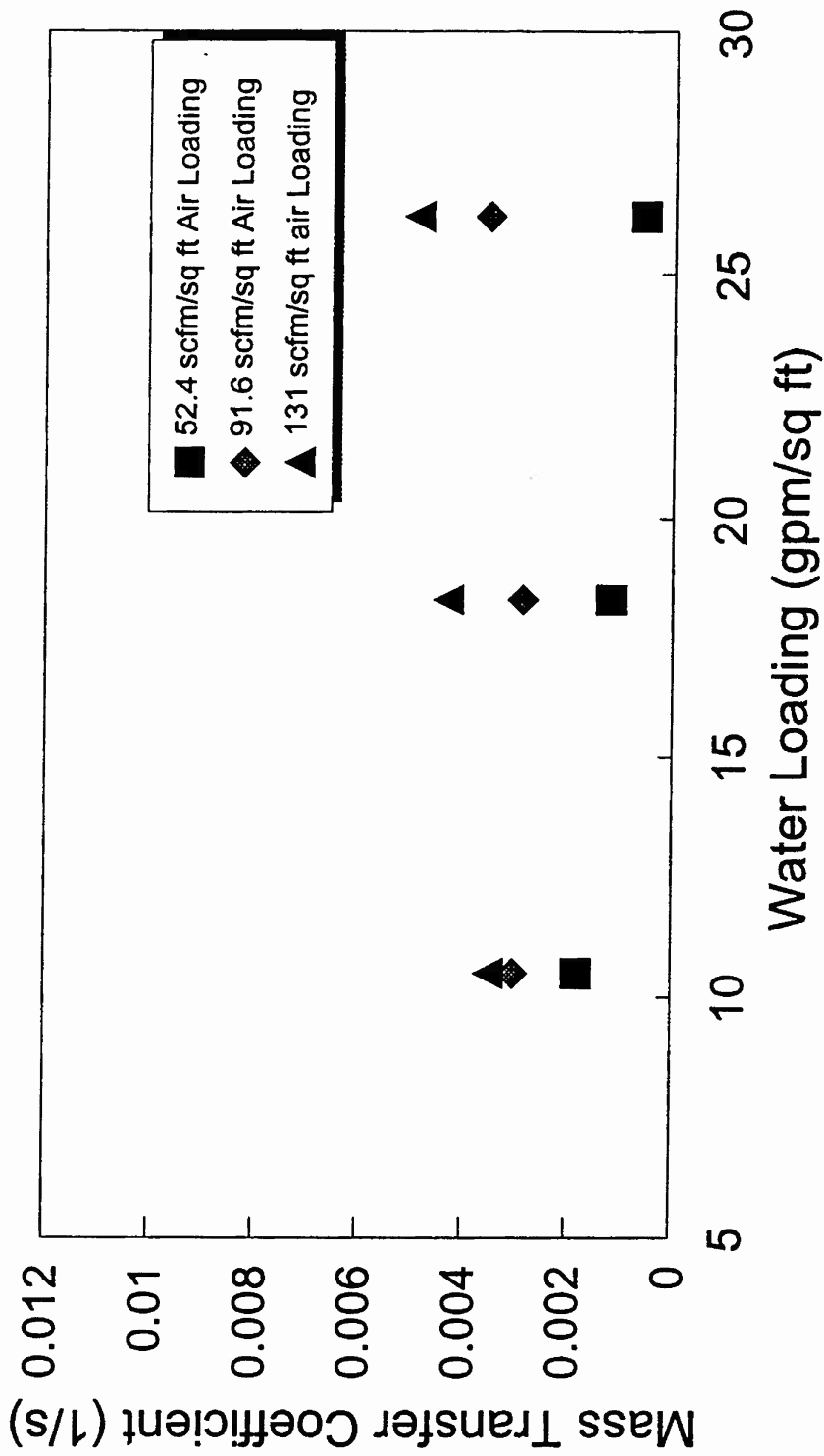


Figure 48. Mass Transfer Coefficients for the CFAS Tower.

## Scaleup - Tower Diameter

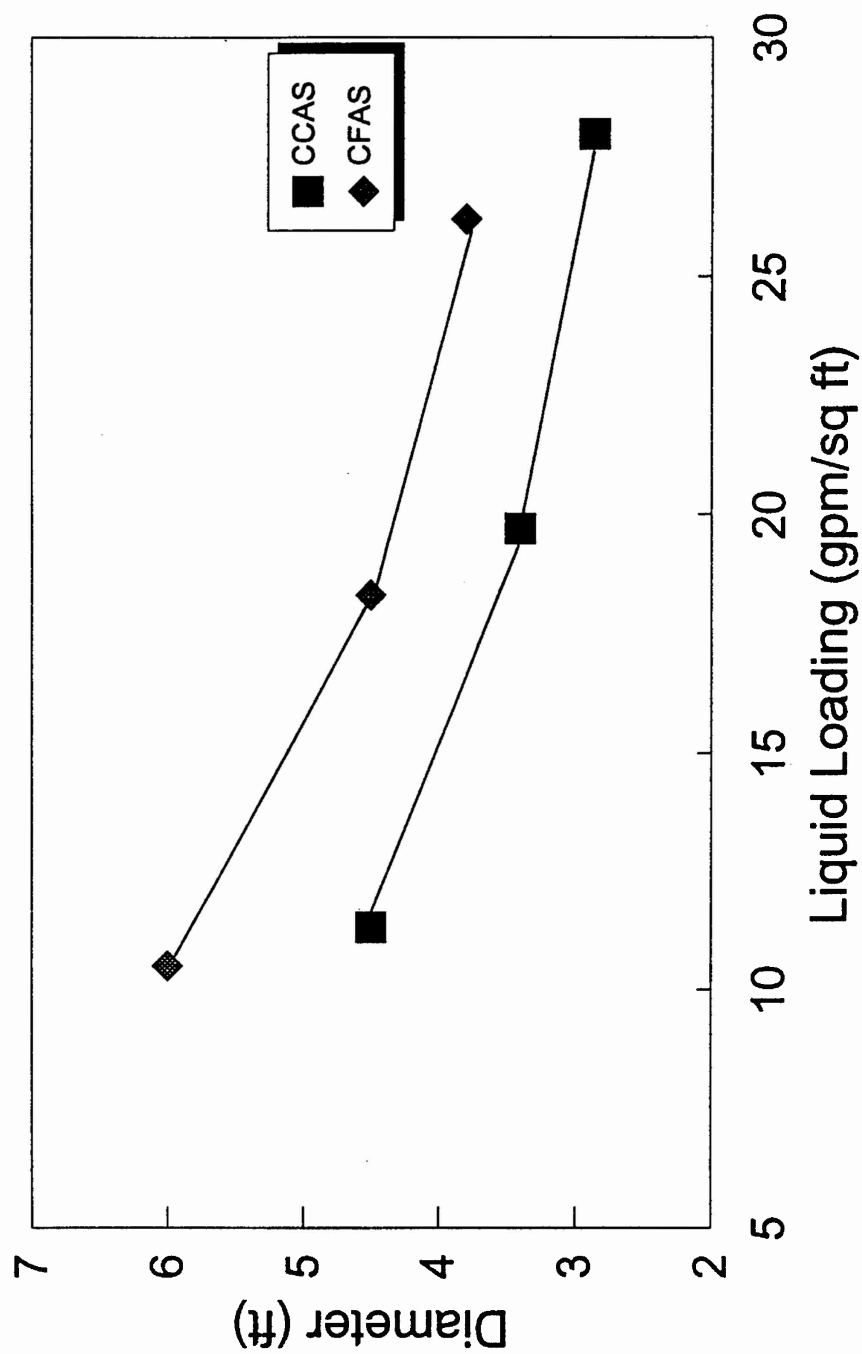


Figure 49. Variation of Tower Diameter for CCAS and CFAS Scaleup.



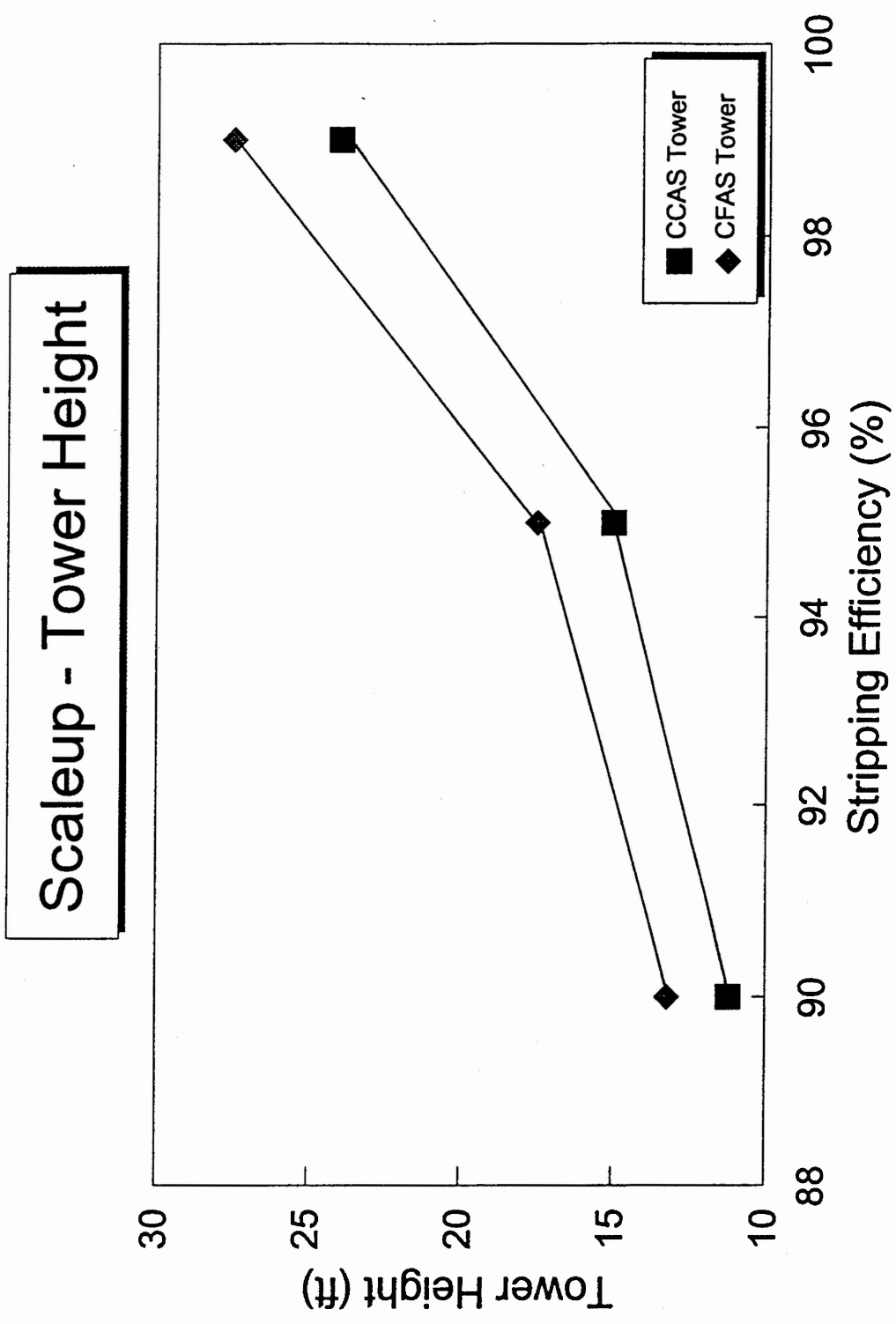


Figure 50. Variation of Tower Height with Stripping Efficiency.

The next step in the scaleup is to determine the size of *air blower* required for the two towers. The following equation by Speece et al. (1987) can be used:

$$\text{Blower horsepower} = \frac{144 Q (p_1 - p_2)}{33,000(E)} \quad (12)$$

where  $Q$  = air flow rate,  $\text{ft}^3/\text{min}$ ;  $p_1 - p_2$  = pressure drop,  $\text{psi}$ ; and  $E$  = blower efficiency (assumed to be 80 percent).

In the 180-gpm design case presented above, we obtained for the CCAS tower an air flow rate of approximately 1,440 scfm and a pressure drop of 2 inches of water (0.12 inch/ft of packing). For the CFAS tower, we obtained an air flow rate of 2,250 scfm and a pressure drop of 0.2 inch of water (0.01 inch/ft of packing). In addition to the pressure drop across the packing, there are other system pressure drops because of piping, elbows, etc. Assuming this additional pressure drop to be 1.0 inch, we get a total pressure drop of 3 inches (CCAS) and 1.2 inches (CFAS). Using Equation 12, we get 0.85 hp for the CCAS tower and 0.53 hp for the CFAS tower. Using the nearest commercially available size of blower (and a safety margin), the projected blower sizes are 1.5 and 1.0 hp for the CCAS and CFAS towers respectively. Thus there is an approximate savings of 0.5 hp using a CFAS tower instead of a CCAS tower.

*Microbial fouling* and *iron* (or other metal) *precipitation* can occur at some sites. Fouling or precipitation may lead to reduced stripping efficiency and downtime for cleaning the towers. The difficulty here is that common sequestrants for iron (e.g., citrate) usually act as nutrients for microbial growth. An on-line hot water recirculation system, such as the one used in this study, can be used. The advantage of the hot water cleaning system is that the towers can be cleaned with minimal downtime, without adding any environmentally incompatible materials to the effluent. Alternatively, special additives developed for such applications can be used (see Appendix K).

## B. CATALYTIC OXIDIZERS

Depending on how the level of VOCs in the airstream from the strippers compares with the state air discharge limits, this air can be either discharged to the ambient directly or treated with a catalytic oxidation unit. All four commercial fixed-bed catalysts\* (UA, HT, AS, and SE) tested during the preliminary test appear suitable for use with an air stripper. Based on the preliminary and extended tests, the scaleup is based on a space velocity of  $5,000 \text{ hr}^{-1}$ , which provided a destruction efficiency of 99 percent. The HT, AS, and SE catalysts were operated at a temperature of  $880^\circ\text{F}$ , while the UA catalyst was operated at  $800^\circ\text{F}$ . These conditions are used as the design basis for a scaleup.

For treating 180 gpm, the air stripper design estimated an air flow rate of 1,440 scfm in the CCAS tower and an air flow rate of 2,250 scfm in the CFAS tower. To obtain a  $5,000\text{-hr}^{-1}$  space velocity, approximately  $17 \text{ ft}^3$  of catalyst would be required in the CCAS tower and  $27 \text{ ft}^3$  in the CFAS tower. This catalyst volume would be required to obtain 99 percent destruction of an airstream containing 2 to 3 ppmv of DCA. The energy input required to heat the airstreams (passing through the catalyst beds) from  $60^\circ\text{F}$  to  $800\text{--}880^\circ\text{F}$  is approximately  $1.617 \times 10^6 \text{ Btu/hour}$  for the CCAS

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\* Catalysts supplied by the University of Akron (UA), Haldor Topsoe (HT), Allied Signal (AS), and Salem Engelhard (SE).

tower (1,440 scfm) and  $2.527 \times 10^6$  Btu/hour for the CFAS tower (assuming 25 percent heat loss from the system).

During the extended test, the KSE photocatalytic oxidizer provided approximately 99 percent destruction efficiency with a space velocity of  $857 \text{ hr}^{-1}$  (49 lamps,  $3.78\text{-ft}^3$  active bed volume) and a preheater temperature of  $160^\circ\text{F}$  (feed air temperature at  $60^\circ\text{F}$ ). For the CCAS tower, in which 1,440 scfm of air needs to be treated at the same space velocity, the active bed volume required is  $101 \text{ ft}^3$  (1307 lamps). The electrical energy input required for these lamps is 52.28 kW. For the CFAS tower, the active bed volume required to treat 2,250 scfm is  $157 \text{ ft}^3$  (2,042 lamps), with an electrical input of 81.68 kW. This assumes that the scaled-up unit will continue to use 40-watt lamps. In actuality, KSE plans to use 60-watt lamps. These lamps will be longer and fewer lamps will be required, but the active bed volume and power consumption will be the same as with the 40-watt lamps. For the preheater, the energy requirement to heat the airstream from  $60^\circ\text{F}$  to  $160^\circ\text{F}$  is  $0.215 \times 10^6$  Btu/hour for the CCAS airstream and  $0.336 \times 10^6$  Btu/hour for the CFAS airstream.

### C. DESIGN SUMMARY

In summary, the design case based on a 180-gpm groundwater treatment plant is provided in Table 10 for the CCAS and CFAS configurations. Although the CFAS tower requires a higher air flow, the pressure drop is lower and a slightly smaller blower is required. However, a larger air volume is sent from the CFAS tower to the catalytic unit for treatment, necessitating a larger catalyst bed and higher energy input.

**TABLE 10. DESIGN SUMMARY FOR CCAS AND CFAS CONFIGURATIONS**

Design Parameter	CCAS	CFAS
<b>Air Stripper</b>		
Water Flow Rate	180 gpm	180 gpm
Inlet Water DCA Concentration	1 ppm	1 ppm
Stripping Efficiency Required	95%	95%
Volumetric Air-to-Water Ratio	60	94
Air Flow Rate	1,440 scfm	2,250 scfm
Cross-Sectional Area of Packing	13.8 ft <sup>2</sup>	17.1 ft <sup>2</sup>
Diameter of Tower	4.2 feet	6.0 feet
Height of Tower	17 feet	17 feet
Expected Pressure Drop (Packing)	2.0 inches	0.2 inch
Blower	1.5 hp	1.0 hp
<b>Conventional Catalytic Oxidizer</b>		
Air Flow Rate	1,440 scfm	2,250 scfm
Inlet Air DCA Concentration	2-3 ppmv	2-3 ppmv
Destruction Efficiency Required	99%	99%
Catalyst Bed Volume	17 ft <sup>3</sup>	27 ft <sup>3</sup>
Operating Temperature	800-880°F	800-880°F
Heat Input to Bed	$1.617 \times 10^6$ Btu/hour	$2.527 \times 10^6$ Btu/hour
<b>Photocatalytic Oxidizer</b>		
Air Flow Rate	1,440 scfm	2,250 scfm
Inlet Air DCA Concentration	2-3 ppmv	2-3 ppmv
Destruction Efficiency Required	99%	99%
Catalyst Bed Volume	101 ft <sup>3</sup>	157 ft <sup>3</sup>
Preheater Temperature	160°F	160°F
Heat Input to Preheater	$0.215 \times 10^6$ Btu/hour	$0.336 \times 10^6$ Btu/hour
Electrical Input to Lamps	52 kW	82 kW

## SECTION IX ECONOMIC ANALYSIS

An economic analysis based on the scaled-up design presented in Section VIII is given below.

### A. AIR-STRIPPING TOWERS

Capital and operating costs were based on a side-by-side comparison between a CCAS and a CFAS tower, either of which can treat 180 gpm of water with 95 percent stripping efficiency.

#### 1. Capital Costs for Full-Scale Air-Stripping Towers

Based on the data collected from the extended test (Section VI), a CCAS tower operating at an air-to-water ratio of 60 and a CFAS tower operating at an air-to-water ratio of 94 will strip 95 percent of DCA out of a water stream with a contaminant loading of approximately 1 ppm. Based on the scaleup results (Section VIII), both full-scale stripping towers operating at these conditions will require approximately 17 feet of packing. The CCAS tower will require a 4.2-foot diameter, whereas the CFAS tower will require a 6.0-foot diameter. Table 11 presents approximate capital costs for the full-scale CCAS and CFAS towers.\* The water pump was sized based on pumping 180 gpm of water to a height of 25 feet. The air blower was sized to deliver 1,440 scfm (1.5 hp) in the CCAS tower and 2,250 scfm (1.0 hp) in the CFAS tower, against pressure drops of 2.0 and 0.2 inches of water, respectively.

TABLE 11. CAPITAL COSTS FOR FULL-SCALE AIR STRIPPERS

Item	CCAS Cost	CFAS Cost
Tower/Ductwork	\$25,000	\$37,500
Installation	\$10,000	\$10,000
Water Pump	\$2,000	\$2,000
Blower	\$5,000	\$4,000
Total	\$42,000	\$53,000

Generally during sizing, the tower height and tower diameter can be adjusted against each other, but the cost trade-off between the two should keep the overall capital cost approximately the same. The tower diameter cannot be increased beyond a certain point (with respect to the tower height) because of the negative effects on liquid distribution across the packing.

#### 2. Operating Costs for Full-Scale Towers

If the air-stripping operation is examined in isolation from catalytic oxidation of the airstreams, the operating costs for both stripping towers will be identical, with the exception of the

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\* Capital cost estimates are based on personal communication with Hydrogroup, Inc., June 1994.

blower. There is a savings of approximately 0.5 hp (0.373 kW) resulting from operating the CFAS tower. Assuming \$0.08 per kW-hour, this translates into a savings of about \$400 per year (365-day operation).

In some cases, additional savings may be realized if there is a fouling advantage in the CFAS tower compared to the CCAS tower. Tests conducted by Louisiana State University (Verma et al., 1994) have indicated that the CFAS tower is much more resistant to fouling than the CCAS tower. Less fouling for the CFAS tower will result in less downtime and a savings in cleaning costs. It is difficult to ascertain the extent of these savings without further data, as the degree of fouling is site-specific. During the extended test at Dover, no microbial fouling was noticed because of the very low organic loading (carbon source). Fouling has been a considerable problem at sites such as at Wurtsmith AFB (Gross and TerMaath, 1985).

## **B. CATALYTIC OXIDATION**

### **1. Capital Costs of Catalytic Units**

Capital costs for catalytic oxidation units are based on several factors such as air flow rate, catalyst bed volume, type of catalyst, heat recovery from exhaust air, pressure drop across the bed, etc. The catalyst manufacturers who participated in this study were asked to provide estimates for scaled-up catalytic units that could treat between 1,440 to 2,250 scfm of air. Initial estimates provided by the manufacturers of the conventional catalytic and photocatalytic units were in the range of \$110,000 to \$250,000. Exact cost comparisons were not conducted because of the varying features offered by different manufacturers. Also, some manufacturers suggested that most units had enough turndown capacity, so that the same size of unit probably would be provided for both the 2,250- and the 1,440-scfm requirement.

### **2. Operating Costs of Catalytic Units**

The main operating cost item associated with catalytic oxidation is the energy input required to heat the incoming air (usually at 60°F) to the catalyst operating temperature (800 to 880°F for the conventional catalysts). For the photocatalytic unit, the energy input takes two forms. One is the energy input required in the preheater to heat the incoming air to 160°F. The other energy input is the electrical requirement of the UV lamps. In Section VII, the energy requirement of the photocatalytic unit was determined.

The operating costs for 99 percent destruction efficiency in the conventional catalytic units are given in Table 12. Similar operating costs for the photocatalytic unit are given in Table 13. The energy costs in these tables do not include the energy requirements of any blowers required to overcome the pressure drop across the catalyst bed systems. The blower size and energy requirement vary with catalyst type and system design.

From these tables, it is apparent that catalytic oxidation, in conjunction with CFAS, has a higher operating cost than catalytic oxidation with CCAS. This is because a larger airstream is generated in the CFAS tower, and this airstream requires a larger energy input to bring it to the catalyst operating temperature.

Depending on contaminant loading and state discharge limits, 99 percent destruction may not be required in all cases. Figure 51 shows the trade-off between the percent destruction required

**TABLE 12. OPERATING COSTS FOR THE CONVENTIONAL CATALYTIC UNITS**

Item	With CCAS	With CFAS
Contaminant	2-3 ppmv DCA	2-3 ppmv DCA
Destruction Efficiency Required	99%	99%
Air Flow Rate	1,440 scfm	2,250 scfm
Inlet Air Temperature	60°F	60°F
Outlet Air Temperature	800-880°F	800-880°F
Heat Input	$1.617 \times 10^6$ Btu/hour	$2.527 \times 10^6$ Btu/hour
Fuel Cost	\$5.50/ $10^6$ Btu/hour	\$5.50/ $10^6$ Btu/hour
Annual Energy Cost*	\$77,900/year	\$121,800/year

\* Not including catalytic unit blower requirements.

**TABLE 13. OPERATING COSTS FOR THE PHOTOCATLYTIC UNIT**

Item	With CCAS	With CFAS
Contaminant	2-3 ppmv DCA	2-3 ppmv DCA
Destruction Efficiency Required	99%	99%
Air Flow Rate	1,440 scfm	2,250 scfm
Inlet Air Temperature	60°F	60°F
Preheater Temperature	160°F	160°F
Heat Input	$0.215 \times 10^6$ Btu/hour	$0.336 \times 10^6$ Btu/hour
Fuel Cost	\$5.50/ $10^6$ Btu	\$5.50/ $10^6$ Btu
Annual Heating cost	\$10,400/year	\$16,200/year
Lamp Electricity Requirement	52 kW	82 kW
Annual Electrical Energy	455,520 kW-hours	718,320 kW-hours
Electrical Cost	\$0.08/kW-hours	\$0.08/kW-hours
Annual Electricity Cost	\$36,400/year	\$57,500/year
Total Annual Energy Costs	\$46,800/year	\$73,700/year

\* Not including catalytic unit blower requirements.

and the corresponding operating costs based on heating energy requirements. The energy costs are based on the temperature-destruction efficiency variation data collected during the preliminary test. As the destruction efficiency required increases, the energy cost increases because the incoming air has to be heated to a higher temperature. Figure 51 provides a direct comparison of the energy cost-operating temperature relationship for the CCAS and CFAS tower airstreams.

Figure 52 shows the variation of energy cost and destruction efficiency for the photocatalytic unit. The energy cost-destruction efficiency data were collected during the extended test.

### **C. ECONOMIC ANALYSIS SUMMARY**

If air stripping is conducted without the need for air treatment, the crossflow air stripper has an operating cost advantage due to the fact that a slightly smaller air blower is required. This savings, though, appears to be small compared with the additional capital cost required to build a CFAS tower. There may be additional savings realized if fouling can be slowed down by using the CFAS tower. This could not be confirmed in this study because neither tower fouled during the extended test. The main advantage of the CFAS tower appears to be its ability to generate high air-to-water ratios at low pressure drops (without flooding), a condition favorable for stripping compounds with low Henry's Law constants.



**Catalytic Oxidation Fuel Cost**  
Full-Scale Fixed-Bed Unit; 5000 1/hr

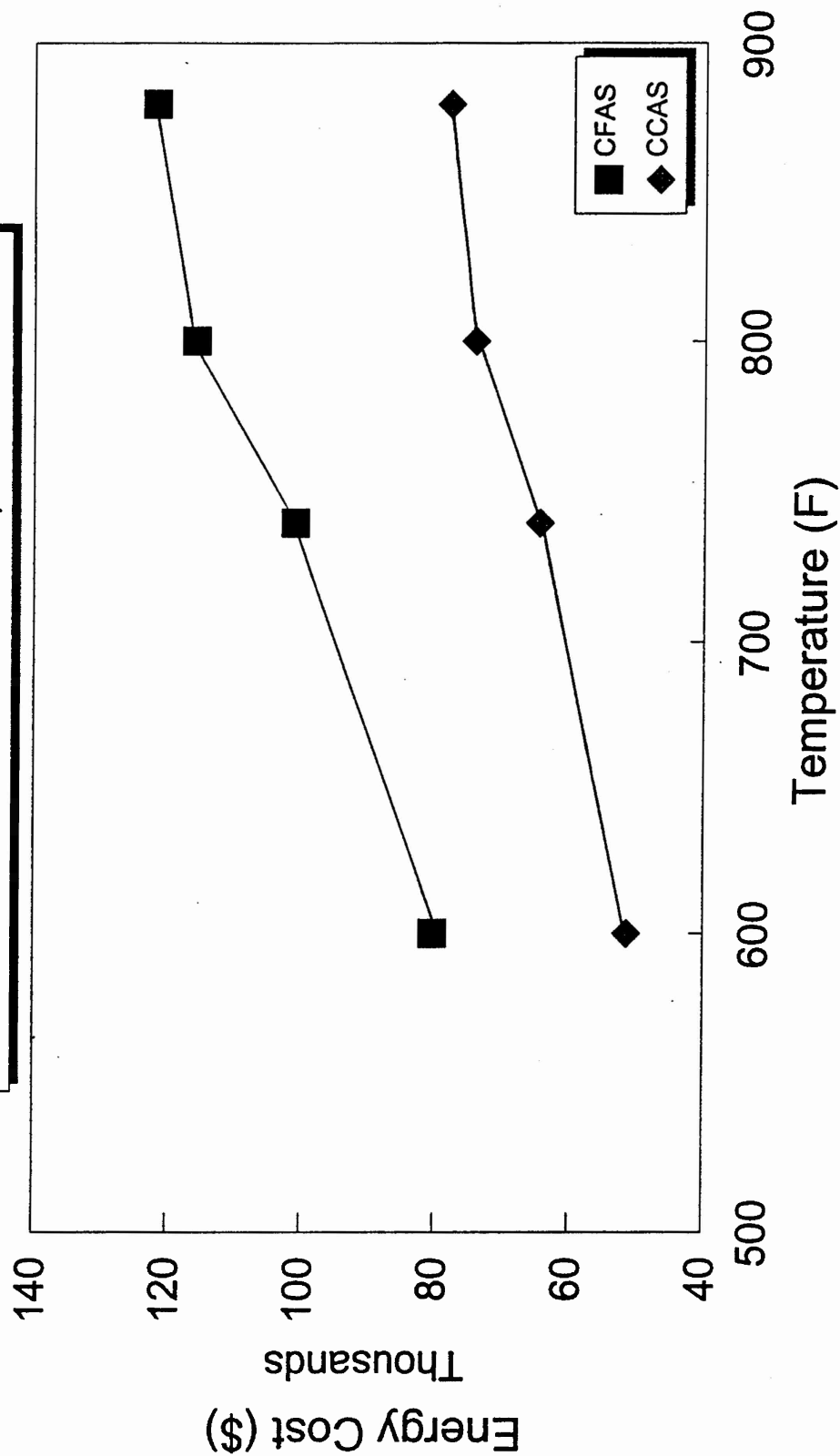


Figure 51. Variation of Heating Costs with Catalyst Operating Temperature.

## Operating Costs for a Photocatalytic Oxidizer

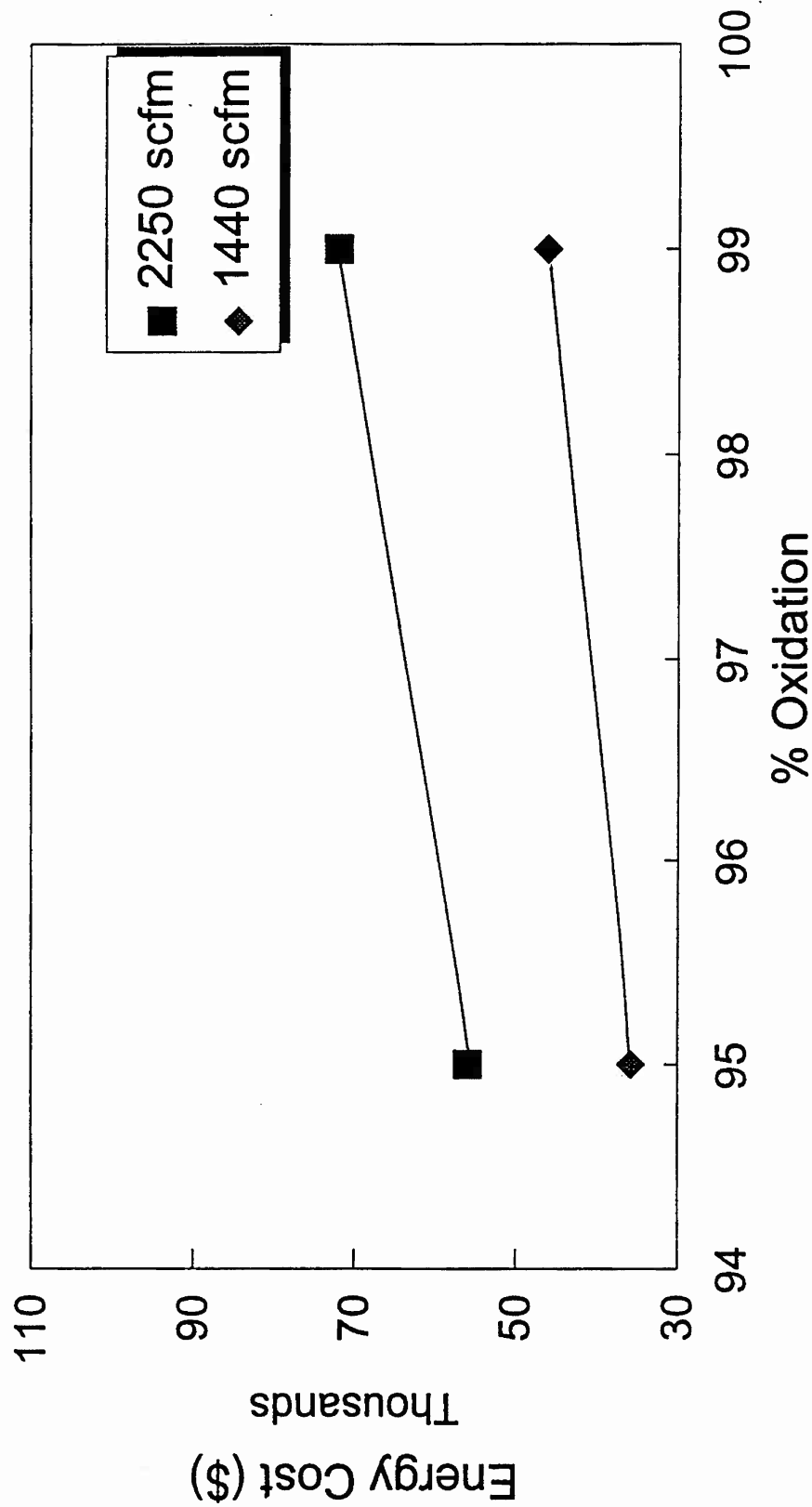


Figure 52. Variation of Energy Costs with Destruction Efficiency for the Photocatalytic Unit.

## SECTION X

### CONCLUSIONS AND RECOMMENDATIONS

The crossflow tower was capable of the same stripping efficiency as the conventional countercurrent tower, but at a higher air-to-water ratio. However, the higher air-to-water ratio required in the CFAS tower is achieved at a pressure drop that is an order of magnitude lower than the pressure drop in the CCAS tower. The CFAS tower, therefore, has the potential to strip compounds with low Henry's Law constant (e.g., DCA). During the extended test, both towers (a CCAS tower and an equivalently sized CFAS tower) consistently demonstrated 95 percent stripping efficiency of DCA at air-to-water ratios of 60 (CCAS) and 94 (CFAS). The corresponding pressure drops were 2.0 (CCAS) and 0.2 inches of water in 17 feet of packing. Higher stripping efficiencies (greater than 95 percent) were obtained in both towers at selected test conditions.

The most widely used correlation for estimating mass transfer coefficient, the Onda's correlation, was found to be overpredicting the coefficient in both countercurrent and crossflow towers. This is consistent with other studies (Munz, 1985) that have found the correlation to overpredict when there is a significant gas-phase resistance to mass transfer. When using the correlation for design purposes, this overprediction should be taken into account.

There is some energy saving from the use of a smaller blower in the CFAS tower. However, the resulting reduction in operating cost does not appear to be high enough to offset (over a reasonable period of time) the additional capital cost of building a CFAS versus a CCAS tower. Also, because the CFAS tower is operated at a much higher air-to-water ratio, a larger volume of contaminated air is generated, although the contaminant loading (mass of contaminant per unit time) in the air from both towers is the same for the same stripping efficiency. If contaminant levels in the airstream are such that the air can be discharged directly to the ambient, then the larger air volume is not a concern. However, if the airstream requires treatment by catalytic oxidation, then operating costs are higher for the CFAS tower because a larger airstream has to be heated to the catalyst operating temperature.

If contaminant levels in the airstream are very low, but regulatory or other concerns still require treatment, then carbon adsorption may be more economical compared to catalytic oxidation (Buck and Hauck, 1992). However, if air stripping followed by carbon adsorption is to be used, then it may be easier to treat the water itself directly with carbon. Previous research efforts by the Air Force have compared carbon treatment of the water with air stripping (Gross and TerMaath, 1985). Air stripping, without treatment of the airstream, was found to be much more economical compared to carbon treatment of the water.

Further research in this area should include evaluation of the CFAS tower with compounds having low Henry's Law constant other than DCA (e.g., chloroform, methyl-ethyl ketone, etc.) to observe any advantages over the CCAS tower. The CFAS tower should be tested at higher air-to-water ratios and higher liquid loading than were achieved in this study. This will enable the estimation of mass transfer coefficients over a wider range of air and water loadings and over a range of contaminants (with different Henry's Law constant). If possible, air-to-water ratios should be taken high enough to estimate the onset of flooding in the CFAS tower. Also, it would be desirable to study the performance of the CCAS and CFAS towers over longer periods of time to observe how the effects of microbial fouling and iron precipitation vary between the two towers.

Several commercial catalysts are available that can effectively treat chlorinated organics in the high-humidity airstreams expected from air stripping operations. In this study, bench-scale fixed-bed catalysts manufactured by University of Akron, Haldor Topsoe A/S, Allied Signal, Inc., and Salem Engelhard demonstrated high destruction efficiencies at the recommended test conditions (800 to 880°F). Over 99 percent destruction efficiency of DCA was achieved under selected conditions. A new fixed-bed catalyst, supplied by a commercial vendor, that also was studied at bench scale, was found to be still in the developmental stage requiring further optimization.

An innovative new photocatalytic oxidation technology, manufactured by KSE, Inc., was tested at pilot scale during the extended test. This unit incorporates a combination of a new catalyst and UV light to oxidize chlorinated organics. This unit performed consistently at the design condition of 95 percent destruction efficiency of DCA during the extended test period. Approximately 99 percent destruction efficiency was achieved under selected test conditions. This catalyst operates at lower temperatures compared to conventional catalysts, resulting in lower operating costs.

Future research should further evaluate the potential for formation of any by-products and products of incomplete combustion in the treated airstream from the catalysts. In this study, a detailed analysis of the airstreams from the bench-scale conventional catalysts was performed, and no significant by-products of concern were detected. However, the low initial concentrations of VOCs in the groundwater (and therefore in the feed air to the catalysts) made detection difficult. The catalysts should be tested at higher concentrations of VOCs to confirm these results. Evaluating the deactivation of the catalysts was not a part of this study.

In general, a combination of air stripping and catalytic oxidation was found to be a good method for remediation of organics in groundwater. The crossflow air stripping concept did not appear to offer any significant cost advantages over conventional air stripping, for the range of test conditions studied. There may be other advantages, however, such as reduced fouling potential and stripping of other compounds with low Henry's Law constant, that could be evaluated in the future.

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## **APPENDIX A**

### **Physical Observations of Air Stripping Operation**

TABLE A-1. PHYSICAL DATA ON AIR-STRIPPING OPERATION

Test ID	Date	Water Flow (gpm)		Air Flow (scfm)		Pressure Drop (in-H2O)		Water Temperature Inlet (F)		Water Temperature Outlet (F)		Air Temperature Inlet (F)		Air Temperature Outlet (F)	
		CC	CF	CC	CF	CC	CF	CC	CF	CC	CF	CC	CF	CC	CF
Alpha D															
02X	09/03/93	20	20	100	100	1	0.2								
4	09/08/93	35	35	104	104	1	0.1	58.6	58.6	58.9	60.6	104.8	103.9		
3	09/08/93	35	35	257	257	7.5	0.2	58.5	58.5	59.2	60.6	91.6	94.9		
6	09/09/93	20	20	182	182	2.7	0.1	59.1	59.1	61	61.8	83.5	83.9		
2	09/10/93	20	20	106	106	1	0.1	59.1	59.1	61.5	63.3	102.3	105.3		
8	09/14/93	35	35	184	184	3.5	0.1	58.4	58.4	59.8	61.1	102.3	103.7		
	09/15/93	35	35	182	182	3.5	0.1	58.7	58.7	60.3	62	98.6	99.7		
	09/15/93	35	35	184	184	3.5	0.1	58.7	58.7	60.9	62.1	103.5	104.6		
1	09/15/93	50	50	184	184	6	0.2	58.9	58.9	62.4	60.4	105.4	106.7		
	09/16/93	50	50	178	178	6	0.2	58.7	58.7	60.5	60.8	86.9	90.6	60.2	60.2
5	09/16/93	50	50	249	249	17.5	0.7	58.8	58.8	59.9	60	84.3	88.6	59.2	59.2
9	09/17/93	50	50	102	102	2	0.1	58.7	58.7	59.4	59.4	82.1	84.6		62.5
	09/17/93	50	50	102	102	2	0.2	58.7	58.7	59.6	59.1	82	84.7	62	62
7	09/20/93	20	20	250	250										
E1	10/14/93	20	20	295	295	6	0.3	59.9	59.9	59.6	60.3	77.5	80.8		
E2	10/14/93	20	20	295	295	8	0.3	60	60	59.4	60	76.4	79.6		
7	10/15/93	20	20	250	250	11.5	5.2	59.6	59.6	59.6	59.8	76.8	77.9		
6	10/15/93	20	20	178	178	8	4.6	59.7	59.7	60.3	60.6	80	81.6		
Alpha 3.56															
18	10/20/93	50	50	101	102	2.5	0.2	58.9	58.9	59	60.2	78.4	79.4	59.4	59.4
10	10/20/93	50	50	174	179	9	0.25	59.3	59.3	59.2	60.2	80.1	83.2	59.5	59.5
13	10/21/93	35	35	103	103	1.5	0.1	59.5	59.5	60.9	61.1	89	89.6	68.6	68.6
17	10/21/93	35	35	180	180	5	0.3	59.6	59.6	61.6	61.6	94.8	93.3	67	67
12	10/21/93	35	35	253	260	9	0.6	59.6	59.6	62.5	61.9	97	99.3	62.7	62.7
11	10/22/93	20	20	100	100	1	0.2	59.8	59.8	58.7	59.2	73	75.3	59.4	59.4
15	10/22/93	20	20	174	174	3.5	0.2	59.9	59.9	58.9	59.6	75.3	79.3	60	60
16	10/25/93	20	20	256	256	12.5	5.4	59.7	59.7	59.6	60.5	92.7	96.6	61	61
14	10/26/93	50	50	245	245	25	6.1	59.3	59.3	58.8	60	77.1	81.1		58.6
		49	49	243	245	25	6.1	59.9	59.5	58.7	60.3	77.3	81.3	58.7	58.7
18	10/27/93	50	50	102	102	4.2	1.3	60.1	60.1	58.6	60.2	84.7	88.6		64.2
10	10/27/93	50	50	173	173	12.5	3.2	59.5	59.5	58.6	59.4	73.3	77.8		58.9

TABLE A-1. (CONTINUED)

Test ID	Date	Water Flow (gpm)		Air Flow (scfm)		Pressure Drop (In-H2O)		Water Temperature Inlet (F)		Water Temperature Outlet (F)		Air Temperature Inlet (F)		Air Temperature Outlet (F)	
		CC	CF	CC	CF	CC	CF	CC	CF	CC	CF	CC	CF	CC	CF
Alpha 7.12															
27	10/29/93	50	50	100	100	4.3	1.3	59.7	59.7	59.7	59.1	81.3	83.9	65.1	65.1
19	10/29/93	50	50	176	176	14	3.5	59.9	59.9	59.9	59.3	84.8	87.5	62.5	62.5
21	11/01/93	35	35	242	242	17.7	6.2	59.8	59.8	59.8	58	65.3	68.4	57	57
26	11/01/93	35	35	170	170	10.5	3.6	59.6	59.6	59.6	56.6	64.8	59.8	56.2	56.2
22	11/01/93	35	35	98	98	3.5	1.3	59.5	59.5	59.5	58.7	59.8	61.3	54.6	54.6
20	11/02/93	20	20	100	100	2.8	1.3	60.1	60.1	60.1	58.8	69.1	73.7	59.2	59.2
20	11/02/93	20	20	100	100	3.6	1.3	60	60	60	58.8	70.5	74.7	59.1	59.1
24	11/02/93	20	20	173	173	8.2	3.4	59.6	59.6	59.6	58.6	68.5	72.1	58.7	58.7
25	11/03/93	20	20	243	243	12.5	5.5	59.5	59.5	59.5	58.2	65.3	67	57	57
23	11/04/93	50	50	242	242	>25.0	5.9	59.5	59.5	59.5	58.5	77	79.4	58.9	58.9
25	11/05/93	20	20	247	247	11.8	5	59.8	59.8	59.8	59.7	76.3	77.9	59	59
25	11/05/93	20	20	249	249	11.8	5.1	60.1	60.1	60.1	60.1	76	76.8	58.9	58.9
22	11/05/93	35	35	100	100	3.7	1.2	59.6	59.6	59.6	58.9	74.7	74.7	59.3	59.3
Alpha 1.78															
2r	11/10/93	20	20	100	100	2	1.2	60	60	60	58.4	73	76.4	59.7	59.7
5r	11/12/93	50	50	250	250	17	8.5	59.5	59.5	59.5	58.7	86.2	91.2	60.1	60.1
1r	11/12/93	50	50	175	175	9.5	4.2	59.6	59.6	59.6	58.7	85.9	90.4	60.7	60.7
9r	11/12/93	50	50	102	102	3	1.3	59.5	59.5	59.5	58.4	84.1	88.2	61.8	61.8
3r	11/13/93	35	35	247	247	12.8	6.6	59.5	59.5	59.5	58.8	75.8	78.8	58.8	58.8
8r	11/13/93	35	35	175	175	7	3.7	59.6	59.6	59.6	58.8	76.5	77.8	58.6	58.6
4r	11/13/93	35	35	101	101	1	0.1	59.6	59.6	59.6	58.8	77	77.2	59	59
7r	11/13/93	20	20	250	250	3.5	0.2	59.6	59.6	59.6	58.8	78.4	78.8	59.2	59.2
6r	11/13/93	20	20	175	175	2.5	0.1	59.7	59.7	59.7	59.3	81.2	82.2	59.5	59.5
X1	11/15/93	20	20	290	290	4	0.1	60.2	60.2	60.2	62.4	93.4	96.8	61.7	61.7
X2	11/15/93	10	10	300	300	2.5	0	61	61	61	66.2	96.8	100.2	63.1	63.1
9π	11/15/93	20	20	250	250	3.5	0.1	61	61	61	62.9	94.4	98.6		



TABLE A-1. (CONTINUED)

Test ID	Date	Water Flow (gpm)		Air Flow (scfm)		Pressure Drop (In-H2O)		Water Temperature Inlet (F)		Water Temperature Outlet (F)		Air Temperature Inlet (F)		Air Temperature Outlet (F)	
		CC	CF	CC	CF	CC	CF	CC	CF	CC	CF	CC	CF	CC	CF
Selected Data From Extended Test Alpha=1.78															
	05/11/94	20	20	160	250	1.5	0.2	58.7	58.7	59.3	62.8	91.5	93.5	62.5	62.5
	05/12/94	20	20	160	251	1.8	0.1	58.8	58.8	58.1	61.2	77.1	81.1	57.7	57.7
	05/17/94	20	20	162	250	2	0.2	59.3	59.3	59.1	60.6	85.9	83.4	60.9	60.9
	05/23/94	21	20	160	250	1.8	0.2	61.6	61.6	65.4	61.5	97.4	95.2	64.6	64.6
	06/01/94	20	20	160	250	1.9	0.2	59.6	59.6	64.8	63.4	98.3	99.3	66.1	66.1
	06/10/94	20	20	160	250	1.8	0.2	58.9	58.9	60.9	65.9	100.8	105.1	66.6	66.6
	06/15/94	20	20	160	250	1.8	0.2	59.5	59.5	65.7	71.9	107	109.8	69.7	69.7
	06/22/94	20	20	160	250	1.8	0.2	59.5	59.5	61.6	66	98.7	103.6	67.7	67.7
	06/29/94	20	20	160	250	1.8	0.2	59.4	59.4	65.5	71.4	100.2	101.7	67.1	67.1
	07/05/94	20	20	160	250	1.8	0.2	59.2	59.2	62.5	68.9	92.1	95.9	63	63
	07/12/94	20	20	160	250	1.8	0.2	59.6	59.6	64.4	64.4	103.6	105.6	68.1	68.1

**APPENDIX B**  
**Minor Contaminants Concentration Data**

**TABLE B-1. PRELIMINARY TEST DATA ON MINOR  
CONTAMINANT REMOVAL BY AIR STRIPPING**

Day	Test ID	Water Flowrate (gpm)	Air Flowrate (scfm)	Volumetric Air/H <sub>2</sub> O Ratio	Chemical	Inlet Water Conc. (ppm)	CC-Outlet Water Conc. (ppm)	CF-Outlet Water Conc. (ppm)
1	2	20	100	37	Vinyl Chloride	5	1	4
					cis-1,2-Dichloroethylene	10	1	1
					Trichloroethylene	50	1	1
					Tetrachloroethylene	35	1	1
6	4	35	100	27	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	6	1	1
					Trichloroethylene	6	1	1
					Tetrachloroethylene	32	1	1
6	3	35	250	53	Vinyl Chloride	4	-	-
					cis-1,2-Dichloroethylene	8	-	-
					Trichloroethylene	6	1	1
					Tetrachloroethylene	42	1	1
7	6	20	175	65	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	8	-	-
					Trichloroethylene	12	-	1
					Tetrachloroethylene	39	1	1
8	2	20	100	37	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	10	-	1
					Trichloroethylene	50	1	1
					Tetrachloroethylene	35	1	1
13	8	35	175	37	Vinyl Chloride	4	-	-
					cis-1,2-Dichloroethylene	5	-	1
					Trichloroethylene	45	1	1
					Tetrachloroethylene	30	1	1
14	1	50	175	26	Vinyl Chloride	1	1	1
					cis-1,2-Dichloroethylene	10	1	1
					Trichloroethylene	50	1	2
					Tetrachloroethylene	40	2	2
14	5	50	250	37	Vinyl Chloride	5	-	-
					cis-1,2-Dichloroethylene	10	-	1
					Trichloroethylene	40	1	1
					Tetrachloroethylene	30	1	1
15	9	50	100	15	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	10	1	2
					Trichloroethylene	45	1	3
					Tetrachloroethylene	35	1	1
18	7	20	250	94	Vinyl Chloride	3	-	-
					cis-1,2-Dichloroethylene	10	1	1
					Trichloroethylene	15	1	1
					Tetrachloroethylene	45	1	2
42	E2	20	295	110	Vinyl Chloride	1	-	1.5
					cis-1,2-Dichloroethylene	7.5	-	1.2
					Trichloroethylene	7.5	1.5	2.5
					Tetrachloroethylene	1.2	1.2	5
43	7	20	250	94	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	8	-	1
					Trichloroethylene	38	1	1
					Tetrachloroethylene	30	1	1
43	6	20	175	65	Vinyl Chloride	1	1	1
					cis-1,2-Dichloroethylene	8	1	1
					Trichloroethylene	40	1	1
					Tetrachloroethylene	30	1	1
48	18	50	100	15	Vinyl Chloride	1	-	1
					cis-1,2-Dichloroethylene	8	1	1
					Trichloroethylene	44	1	1
					Tetrachloroethylene	36	1	1
49	13	35	100	21	Vinyl Chloride	2	-	-
					cis-1,2-Dichloroethylene	8	1	1
					Trichloroethylene	10	1	1
					Tetrachloroethylene	36	1	1
49	17	35	175	37	Vinyl Chloride	2	-	-
					cis-1,2-Dichloroethylene	8	-	1
					Trichloroethylene	10	1	1
					Tetrachloroethylene	34	1	1

TABLE B-1. (CONTINUED)

Day	Test ID	Water Flowrate (gpm)	Air Flowrate (scfm)	Volumetric Air/H <sub>2</sub> O Ratio	Chemical	Inlet Water Conc. (ppm)	CC-Outlet Water Conc. (ppm)	CF-Outlet Water Conc. (ppm)
49	12	35	250	53	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	8	-	-
					Trichloroethylene	10	1	1
					Tetrachloroethylene	34	1	1
50	11	20	100	37	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	8	-	-
					Trichloroethylene	6	-	-
					Tetrachloroethylene	26	1	-
50	15	20	175	65	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	8	-	-
					Trichloroethylene	14	-	-
					Tetrachloroethylene	38	-	-
53	16	20	250	94	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	8	-	1
					Trichloroethylene	8	-	1
					Tetrachloroethylene	30	-	1
54	14	50	250	37	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	6	-	1
					Trichloroethylene	40	1	1
					Tetrachloroethylene	30	2	1
55	18	50	100	15	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	8	1	1
					Trichloroethylene	40	1	1
					Tetrachloroethylene	30	1	1
55	10	50	175	26	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	8	-	1
					Trichloroethylene	40	1	1
					Tetrachloroethylene	30	1	1
57	27	50	100	15	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	4	1	2
					Trichloroethylene	10	1	-
					Tetrachloroethylene	30	1	3
57	19	50	175	26	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	8	-	1
					Trichloroethylene	52	1	1
					Tetrachloroethylene	40	1	1
60	21	35	250	53	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	6	-	1
					Trichloroethylene	36	1	1
					Tetrachloroethylene	28	1	1
60	26	35	175	37	Vinyl Chloride	1	1	-
					cis-1,2-Dichloroethylene	8	1	1
					Trichloroethylene	38	1	1
					Tetrachloroethylene	28	1	1
60	22	35	100	21	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	-	-	1
					Trichloroethylene	45	1	1
					Tetrachloroethylene	35	1	1
61	20	20	100	37	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	8	-	1
					Trichloroethylene	40	1	1
					Tetrachloroethylene	30	1	1
61	24	20	175	65	Vinyl Chloride	2	-	-
					cis-1,2-Dichloroethylene	8	-	-
					Trichloroethylene	40	1	1
					Tetrachloroethylene	32	1	1
62	25	20	250	94	Vinyl Chloride	4	-	-
					cis-1,2-Dichloroethylene	12	-	-
					Trichloroethylene	52	1	1
					Tetrachloroethylene	44	1	1
63	23	50	250	37	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	8	1	1
					Trichloroethylene	42	1	1
					Tetrachloroethylene	32	1	1

TABLE B-1. (CONTINUED)

Day	Test ID	Water Flowrate (gpm)	Air Flowrate (scfm)	Volumetric Air/H <sub>2</sub> O Ratio	Chemical	Inlet Water Conc. (ppm)	CC-Outlet Water Conc. (ppm)	CF-Outlet Water Conc. (ppm)
64	25	20	250	94	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	10	-	-
					Trichloroethylene	45	-	1
					Tetrachloroethylene	30	-	-
64	22	35	100	21	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	8	-	1
					Trichloroethylene	42	-	1
					Tetrachloroethylene	35	-	1
69	2r	20	100	37	Vinyl Chloride	-	-	-
					cis-1,2-Dichloroethylene	6	-	-
					Trichloroethylene	30	-	1
					Tetrachloroethylene	24	1	1
71	5r	50	250	37	Vinyl Chloride	1	-	1
					cis-1,2-Dichloroethylene	8	-	1
					Trichloroethylene	48	-	1
					Tetrachloroethylene	38	1	1
71	1r	50	175	26	Vinyl Chloride	1	1	-
					cis-1,2-Dichloroethylene	1	-	1
					Trichloroethylene	2	1	1
					Tetrachloroethylene	40	1	1
71	9r	50	100	15	Vinyl Chloride	1	1	1
					cis-1,2-Dichloroethylene	8	1	2
					Trichloroethylene	42	1	2
					Tetrachloroethylene	1	1	1
72	3r	35	250	53	Vinyl Chloride	4	1	1
					cis-1,2-Dichloroethylene	10	1	1
					Trichloroethylene	48	1	1
					Tetrachloroethylene	1	1	1
72	8r	35	175	37	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	8	-	1
					Trichloroethylene	34	-	1
					Tetrachloroethylene	1.8	-	1
72	4r	35	100	21	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	8	-	-
					Trichloroethylene	42	-	1
					Tetrachloroethylene	1.3	-	1
72	7r	20	250	94	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	8	-	-
					Trichloroethylene	44	-	-
					Tetrachloroethylene	1.4	-	-
72	6r	20	175	65	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	7	-	-
					Trichloroethylene	38	-	5
					Tetrachloroethylene	30	-	-
74	X1	20	290	108	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	6	-	-
					Trichloroethylene	32	1	1
					Tetrachloroethylene	26	1	1
74	X2	10	300	224	Vinyl Chloride	1	-	-
					cis-1,2-Dichloroethylene	7	-	-
					Trichloroethylene	38	2	2
					Tetrachloroethylene	30	2	1
75	7r	20	250	94	Vinyl Chloride	2	-	-
					cis-1,2-Dichloroethylene	10	-	-
					Trichloroethylene	38	-	12
					Tetrachloroethylene	30	1	1

**TABLE B-2. EXTENDED TEST DATA ON TRICHLOROETHYLENE (TCE)  
REMOVAL BY AIR STRIPPING**

Date	Day	TCE In Inlet Water (ppb)	TCE Conc in Outlet Water (ppb)		Removal Efficiency*	
			CC	CF	CC	CF
05/11/94	1	71	3	1	95.8	98.6
05/12/94	2	73	3	3	95.9	95.9
05/13/94	3	67	0	1	100.0	98.5
05/15/94	5	50	1	4	98.0	92.0
05/17/94	7	43	0	1	100.0	97.7
05/19/94	9	38	1	2	97.4	94.7
05/23/94	13	50	1	0	98.0	100.0
05/24/94	14	28	0	0	100.0	100.0
05/25/94	15	44	0	0	100.0	100.0
05/27/94	17	47	0	0	100.0	100.0
05/31/94	21	46	0	0	100.0	100.0
06/01/94	22	37	0	0	100.0	100.0
06/10/94	31	50	0	0	100.0	100.0
06/12/94	33	59	0	0	100.0	100.0
06/13/94	34	42	0	0	100.0	100.0
06/15/94	36	43	0	0	100.0	100.0
06/17/94	38	39	0	0	100.0	100.0
06/19/94	40	40	0	0	100.0	100.0
06/22/94	43	33	0	0	100.0	100.0
06/28/94	49	27	0	0	100.0	100.0
06/30/94	51	30	0	0	100.0	100.0
07/02/94	53	37	0	0	100.0	100.0
07/04/94	55	38	0	0	100.0	100.0
07/07/94	58	33	0	0	100.0	100.0
07/12/94	63	33	0	0	100.0	100.0
07/12/94	63a	33	0	1	100.0	97.0

\* A 100 percent removal efficiency indicates that the TCE concentration in the outlet water was below the detection limit of 1 ppb.

**TABLE B-3. EXTENDED TEST DATA ON PERCHLOROETHYLENE (PCE) REMOVAL BY AIR STRIPPING**

Date	Day	PCE In Inlet Water (ppb)	PCE Conc in Outlet Water (ppb)		Removal Efficiency*	
			CC	CF	CC	CF
05/11/94	1	72	3	1	95.8	98.6
05/12/94	2	72	2	5	97.2	93.1
05/13/94	3	68	1	1	98.5	98.5
05/15/94	5	46	2	0	95.7	100.0
05/17/94	7	38	1	0	97.4	100.0
05/19/94	9	33	0	0	100.0	100.0
05/23/94	13	45	2	2	95.6	95.6
05/24/94	14	34	2	0	94.1	100.0
05/25/94	15	43	0	0	100.0	100.0
05/27/94	17	43	0	1	100.0	97.7
05/31/94	21	39	2	2	94.9	94.9
06/01/94	22	51	0	0	100.0	100.0
06/10/94	31	42	0	0	100.0	100.0
06/12/94	33	50	0	0	100.0	100.0
06/13/94	34	40	1	0	97.5	100.0
06/15/94	36	41	0	0	100.0	100.0
06/17/94	38	36	0	0	100.0	100.0
06/19/94	40	38	0	0	100.0	100.0
06/22/94	43	33	0	0	100.0	100.0
06/23/94	44	43	0	0	100.0	100.0
06/28/94	49	26	0	0	100.0	100.0
06/30/94	51	34	0	0	100.0	100.0
07/02/94	53	34	0	0	100.0	100.0
07/04/94	55	37	0	0	100.0	100.0
07/07/94	58	33	0	0	100.0	100.0
07/12/94	63	34	3	1	91.2	97.1
07/12/94	63a	30	1	1	96.7	96.7
07/13/94	64	42	1	2	97.6	95.2
07/13/94	64a	39	0	0	100.0	100.0

\* A 100 percent removal efficiency indicates that the PCE concentration in the outlet water was below the detection limit of 1 ppb.

**APPENDIX C**  
**Statistical Analysis**



## APPENDIX C

### STATISTICAL ANALYSIS

#### STATISTICAL MODELING FOR AIR STRIPPING: PRELIMINARY TEST RESULTS

The primary objective of the stripping tower study was to examine differences between the two stripping towers used in the study. Two specific questions were of interest:

- Are there any differences in the response variables between the four crossflow tower configurations, and
- Is the crossflow tower more efficient than the countercurrent tower?

Two dependent variables were used in the statistical analyses: stripping efficiency and pressure change. In addition, the relationship between these three dependent variables and several other variables (air flow rate, water flow rate, air-to-water mass balance, inlet air concentration, inlet water concentration, and time) were examined.

The statistical analysis to determine the relationships between the dependent and predictor variables was divided into three steps. First, correlations between the dependent variables and the predictor variables were calculated to determine the predictor variables to include in the general linear models. The correlations between the predictor variables were also calculated in order to eliminate collinear variables. Second, a regression model was applied to determine which variables were significantly related to the dependent variables and which could be eliminated because of interdependence. Finally, multiple comparisons were performed to determine significant differences between the stripping towers using the residuals of the multiple regression model resulting from the previous step. Two sets of multiple comparisons were performed. The four crossflow tower configurations were compared to each other using Tukey's procedure for all pairwise comparisons, and each crossflow tower configuration was compared to the matching countercurrent tower configuration using Dunnett's procedure for comparing treatments with a control.

Table C-1 presents the correlations between the three dependent variables and nine predictor variables. Removal efficiency was strongly correlated with water flow rate, air flow rate, outlet water concentration, and air-to-water ratio.

**TABLE C-1. CORRELATIONS BETWEEN DEPENDENT AND PREDICTOR VARIABLES FOR STRIPPING TOWER STUDY**

Variable	Removal Efficiency	Pressure Change
Water Flow rate	-0.722	0.068
Air Flow rate	0.618	0.648
Pressure Change	0.281	1.000
Inlet Water Concentration	0.113	-0.171
Inlet Air Concentration	0.128	0.292
Outlet Water Concentration	-0.725	-0.350
Outlet Air Concentration	-0.282	-0.274
Air-to-Water Ratio	0.344	-0.040
Study Day	-0.139	0.395

Because the outlet water concentration is used to calculate the stripping efficiency, it was removed from consideration as a prediction variable. Pressure change was strongly correlated with air flow rate, outlet water concentration, and time. Because outlet water concentration and air flow rate are strongly correlated, the former variable was eliminated from consideration in the multiple regressions for pressure change. Both outlet concentrations are strongly correlated with the two flow rates, so they were also eliminated from consideration.

In the second step of the analysis, a multiple regression model was fit to each dependent variable using the previously identified predictor variables. Table C-2 shows the results of the multiple regression procedure. Removal efficiency varied directly with the air-to-water ratio and the air flow rate, and inversely with the water flow rate. Pressure drop varied directly with the air flow rate, but was lower later in the study.

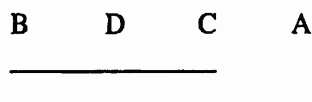
The final step of the stripping tower analysis was to determine whether there were any statistically significant differences between the stripping towers with respect to the three dependent variables. Tukey multiple comparisons showed a significant difference between baffle configurations B ( $\alpha = 3.56$ ) and A ( $\alpha = D$ ). However, neither configuration B nor A differed significantly from configurations C ( $\alpha = 7.12$ ) and D ( $\alpha = 1.78$ ). Figure C-1 shows this overlay schematically. Those battle configurations which are not significantly different are connected with lines. No significant differences were found between the four crossflow tower baffle configurations with respect to pressure drop or the mass transfer coefficient. Dunnett's multiple comparisons test showed no significant differences between the crossflow baffle configurations for any of the three dependent variables.

**TABLE C-2. MULTIPLE REGRESSION RESULTS FOR THE AIR STRIPPING TEST:  
PARAMETER ESTIMATES FOR THE COVARIATES**

Parameter	Estimate	Std Error	p-value
<b>Dependent Variable: Removal Efficiency</b>			
Intercept	0.98	0.194	0.000
Air-to-Water Ratio	134	50.9	0.012
Air Flow rate	0.0091	0.0008	0.000
Water Flow rate	-0.0576	0.0039	0.000
<b>Dependent Variable: Pressure Change</b>			
Intercept	-3.15	0.917	0.006
Air Flow rate	0.0242	0.0044	0.000
Study Day	0.0344	0.0118	0.006
<b>Dependent Variable: Mass Transfer Coefficient</b>			
Intercept	0.0528	0.00587	0.000
Water Flow rate	-0.00155	0.00012	0.000
Air Flow rate	0.00030	0.00002	0.000

**STATISTICAL MODELING FOR CATALYTIC OXIDATION:  
PRELIMINARY TEST RESULT**

Statistical analysis for the catalytic oxidation tests was similar to that conducted for the air stripping test. The primary objective was to determine whether there were any differences among the four commercial catalysts. Two dependent variables were of interest in this study: the efficiency of the oxidation process and the pressure change during the process. Other variables whose relationships to the dependent variables were also of interest were space velocity, temperature, inlet air concentration, and time. The three steps used in the analysis of the stripping tower data were also used here.



**Figure C-1. Tukey Multiple Comparison Results for Crossflow Stripping Tower  
Baffle Configurations Based on Stripping Efficiency.**

Table C-3 shows the correlations between the two dependent variables and the six predictor variables used in the catalytic oxidation testing. Strong correlations were found between removal efficiency and the variables of temperature, space velocity, inlet air concentration, outlet air concentration, and study day. The correlation coefficient between the study day and the temperature was  $-0.92$ , indicating that these two predictor variables are highly interdependent. This strong correlation results from the design of the tests. All experiments at the highest level of temperature were conducted first, followed by all the experiments at the intermediate temperature and then all the experiments at the lowest temperature. It was assumed that the strong correlation between the removal efficiency and the study day was a residual effect of the relationship between the removal efficiency and the temperature, so study day was eliminated from the multiple regression step. The inlet and outlet air concentrations were both strongly correlated to the temperature and study day, so they were also removed from consideration. A strong correlation was also found between the pressure change and the space velocity.

**TABLE C-3. CORRELATIONS BETWEEN DEPENDENT AND PREDICTOR VARIABLES FOR CATALYST STUDY**

Variable	Removal Efficiency	Pressure Change
Temperature	0.680	0.046
Space Velocity	$-0.379$	0.524
Pressure Change	0.128	1.000
Inlet Air Concentration	$-0.317$	$-0.022$
Outlet Air Concentration	$-0.884$	$-0.081$
Study Day	$-0.680$	$-0.164$

Table C-4 shows the results of the multiple regression procedure for Phase II. Efficiency was greater when temperature was higher and when the space velocity was lower. Pressure change varied directly with space velocity.

The results of the Tukey multiple comparisons applied to the residuals of the multiple regression models indicated differences between the catalysts. Figure C-2 shows schematically the significant differences in catalysts with respect to the efficiency. The lines join catalysts that were not found to be significantly different. Catalyst UA performed the best, Catalyst SE second best, followed by the remaining catalysts (AS and HT) which differed insignificantly from each other. Figure C-3 shows

**TABLE C-4. MULTIPLE REGRESSION RESULTS FOR THE CATALYTIC OXIDATION TESTING: PARAMETER ESTIMATES FOR COVARIATES**

Parameter	Estimate	Std Error	p-value
<b>Dependent Variable: Removal Efficiency</b>			
Intercept	-2.2	1.02	0.029
Temperature	0.00821	0.00132	0.000
Space Velocity	-0.00016	0.00005	0.002
<b>Dependent Variable: Pressure Change</b>			
Intercept	-0.0354	0.136	0.796
Space Velocity	0.00007	0.00002	0.001

schematically the significant differences between catalysts with respect to pressure change. Catalyst UA was significantly higher than the other three catalysts; catalyst AS was significantly lower than Catalyst UA, significantly higher than Catalyst SE, but not significantly different from Catalyst HT. Catalysts HT and SE were not significantly different.

UA    SE    AS    HT

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**Figure C-2. Tukey Multiple Comparison Results for Catalysts Based on Removal Efficiency**

UA    AS    HT    SE

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**Figure C-3. Tukey Multiple Comparison Results for Catalysts Based on Pressure Change**

**APPENDIX D**  
**Physical Observations of Catalyst Testing**

TABLE D-1. PHYSICAL OBSERVATIONS OF CATALYST OPERATION — PRELIMINARY TEST

Test ID	Date	Catalyst ID	Space Velocity (1/hr)	Flowrate (L/min)	Core Bed		Furnace		Preheater		Catalyst Pressure Drop (in H <sub>2</sub> O)	Inlet Air		Outlet Air	
					Temp (F)	Temp (F)	Controller Temp (F)	Controller Temp (F)	Controller Temp (F)	Controller Temp (F)		Temp (F)	Temp (F)	Temp (F)	Temp (F)
1	09/28/93	AS	10000	3.3	599	622		225			0.0	224		441	
1	09/28/93	UA	10000	3.0	600	660		145			1.0	146		512	
1	09/28/93	HT	10000	3.3	600	657		226			0.5	226		497	
1	09/28/93	SE	10000	2.4	601	622		225			0.0	224		488	
1	09/28/93	UA	10000	3.0	601	659		150			1.5	150		516	
1	09/28/93	AS	10000	3.7	598	622		224			0.0	228		442	
1	09/28/93	AS	10000	3.8	599	622		226			0.0	230		444	
8	09/29/93	AS	10000	3.7	739	752		226			0.2	231		541	
8	09/29/93	UA	10000	3.0	739	790		182			1.9	183		621	
8	09/29/93	HT	10000	3.3	739	807		193			0.5	192		613	
8	09/29/93	SE	10000	6.4	740	758		228			0.3	228		594	
5	09/30/93	UA	10000	4.2	740	778		227			0.8	227		567	
3	10/04/93	UA	5000	4.3	800	836		265			0.9	265		623	
3	10/04/93	HT	5000	4.3	880	939		288			0.3	288		672	
3	10/04/93	AS	5000	4.3	880	884		227			0.4	231		664	
3	10/04/93	SE	5000	3.2	877	938		289			0.0	289		666	
9	10/05/93	UA	2500	2.2	800	859		370			0.4	375		587	
9	10/05/93	HT	2500	2.2	880	963		405			0.0	404		643	
9	10/05/93	AS	2500	2.2	880	909		328			0.2	331		623	
9	10/05/93	SE	2500	1.6	880	913		394			0.0	395		585	
6	10/06/93	HT	10000	8.5	880	939		230			0.5	229		713	
6	10/06/93	UA	10000	8.5	801	843		200			1.8	201		667	
6	10/06/93	SE	10000	6.3	880	909		231			0.3	231		714	
6	10/06/93	AS	10000	8.9	879	922		163			0.7	168		736	
8	10/07/93	UA	10000	8.5	740	783		191			1.7	191		620	
8	10/07/93	HT	10000	8.5	739	794		225			0.5	224		603	
8	10/07/93	AS	10000	8.9	740	787		151			0.6	156		633	
8	10/07/93	SE	10000	6.4	740	773		225			0.3	224		608	

TABLE D-1. (CONTINUED)

Test ID	Date	Catalyst ID	Space Velocity (1/hr)	Flowrate (L/min)	Core		Furnace Controller Temp (F)	Preheater Controller Temp (F)	Catalyst Pressure Drop (in H2O)	Inlet Air		Outlet Air	
					Bed Temp (F)					Temp (F)	Temp (F)	Temp (F)	Temp (F)
5	10/08/93	UA	5000	4.5	740	779	272	0.8	272	576			
5	10/08/93	HT	5000	4.5	740	786	270	0.3	269	565			
5	10/08/93	AS	5000	4.5	740	741	215	0.4	220	567			
5	10/08/93	SE	5000	3.2	740	772	295	0.0	295	542			
2	10/11/93	UA	2500	2.0	740	800	336	0.4	351	545			
2	10/11/93	SE	2500	1.6	740	780	334	0.0	334	490			
2	10/11/93	HT	2500	2.0	741	804	355	0.0	355	540			
2	10/11/93	AS	2500	2.0	739	778	281	0.2	286	508			
4	10/12/93	UA	2500	2.0	601	658	313	0.4	313	446			
4	10/12/93	HT	2500	2.0	600	659	308	0.0	308	442			
4	10/12/93	AS	2500	2.0	600	625	250	0.2	254	428			
4	10/12/93	SE	2500	1.6	599	643	297	0.0	297	400			
7	10/12/93	UA	5000	4.5	600	639	205	0.8	205	463			
7	10/12/93	SE	5000	3.2	601	637	235	0.0	234	439			
7	10/12/93	HT	5000	4.5	599	641	224	0.0	226	453			
7	10/12/93	AS	5000	4.5	600	614	163	0.3	167	449			
1	10/13/93	UA	10000	8.5	600	655	153	1.2	152	505			
1	10/13/93	HT	10000	8.5	600	649	225	0.3	225	483			
1	10/13/93	SE	10000	6.4	600	641	225	0.1	225	487			
1	10/13/93	AS	10000	8.9	601	672	122	0.6	127	507			
09r	11/11/93	UA	2500	2.0	799	856	381	0.2	369	588			
09r	11/11/93	SE	2500	1.6	881	910	350	0.0	350	591			
09r	11/11/93	AS	2500	2.0	880	911	328	0.2	330	621			
09r	11/11/93	HT	2500	2.0	880	959	413	0.0	414	647			
04r	11/12/93	SE	2500	1.6	599	647	282	0.0	281	390			
09rr	11/12/93	HT	2500	2.0	879	958	405	0.0	404	648			
02r	11/12/93	SE	2500	1.6	740	771	279	0.0	278	512			



**TABLE D-2. PHYSICAL OBSERVATIONS OF CATALYST  
OPERATION — EXTENDED TEST**

Test ID	Date	Catalyst ID	Space Velocity (1/hr)	Flowrate (L/min)	Core Bed Temp (F)	Furnace Controller Temp (F)	Preheater Controller Temp (F)	Catalyst Pressure Drop (in H <sub>2</sub> O)	Inlet Air Temp (F)	Outlet Air Temp (F)
Select Data from Extended Test										
extend	05/11/94	A	5000	4.4	800	836	259	0.5	258	-
extend		B	5000	4.4	482	499	227	0.9	226	-
extend		C	5000	4.4	879	899	233	0.4	237	-
extend		D	5000	3.2	880	880	300	0.1	300	-
extend	05/12/94	A	5000	4.4	796	836	230	0.5	230	616
extend		B	5000	4.4	480	498	226	0.8	226	354
extend		C	5000	4.4	878	900	212	0.6	217	652
extend		D	5000	3.2	878	887	260	0.1	260	628
extend	05/17/94	A	5000	4.4	797	843	226	0.5	226	611
extend		B	5000	4.4	485	484	226	0.1	225	362
extend		C	5000	4.4	880	907	217	0.5	222	647
extend		D	5000	3.2	880	889	288	0.1	287	603
extend	05/23/94	A	5000	4.5	802	842	256	0.6	257	622
extend		B	5000	4.5	480	486	229	0.5	229	362
extend		C	5000	4.5	881	905	241	0.4	245	657
extend		D	5000	3.3	881	888	311	0.2	310	621
extend	06/01/94	A	5000	4.4	801	258	259	0.5	258	625
extend		B	5000	4.5	481	229	229	0.1	229	370
extend		C	5000	4.5	881	235	231	0.4	235	662
extend		D	5000	3.2	879	270	271	0.1	270	634
extend	06/10/94	A	5000	4.5	797	844	292	0.6	294	619
extend		B	5000	4.5	569	586	239	0.4	239	437
extend		C	5000	4.5	877	908	256	0.4	261	654
extend		D	5000	3.2	878	604	327	0.1	326	611
extend	06/15/94	A	5000	4.5	801	844	290	0.5	288	625
extend		B	5000	4.5	566	587	246	0.3	244	437
extend		C	5000	4.5	883	907	254	0.4	257	665
extend		D	5000	3.2	880	888	320	0.2	319	613
extend	06/22/94	A	5000	4.5	803	844	230	0.4	229	629
extend		B	5000	4.5	577	596	231	0.4	230	433
extend		C	5000	4.5	868	907	231	0.1	236	626
extend		D	5000	3.2	878	888	294	0.5	294	599
extend	06/29/94	A	5000	4.5	803	844	285	0.4	285	632
extend		B	5000	4.5	560	588	246	0.4	245	435
extend		C	5000	4.5	884	907	254	0.4	258	665
extend		D	5000	3.2	875	888	327	0.1	327	613
extend	07/05/94	A	5000	4.5	800	844	279	0.5	278	624
extend		B	5000	4.5	562	589	243	0.4	242	434
extend		C	5000	4.5	879	907	253	0.5	257	656
extend		D	5000	3.2	879	888	330	0.1	330	605

## **APPENDIX E**

### **Catalyst Test: Influent and Effluent Concentration Data for DCE, TCE, and PCE**

**TABLE E-1. INCOMING AND OUTGOING AIR CONCENTRATIONS  
FOR DICHLOROETHYLENE, TRICHLOROETHYLENE,  
AND PERCHLOROETHYLENE**

Test ID	Date	Catalyst ID	Bed Temp (F)	Space Velocity (1/hr)	Inlet DCE Conc. (ppb)	Outlet DCE Conc. (ppb)	Inlet TCE Conc. (ppb)	Outlet TCE Conc. (ppb)	Inlet PCE Conc. (ppb)	Outlet PCE Conc. (ppb)
1	09/28/93	AS	600	10000	52	1	12	1	147	1
1	09/28/93	UA	600	10000	52	3	12	81	147	<1
1	09/28/93	HT	600	10000	52	3	12	109	147	<1
1	09/28/93	SE	600	10000	52	5	12	181	147	125
1	09/28/93	UA	600	10000	52	3	12	91	147	<1
1	09/28/93	AS	600	10000	52	2	12	<1	147	<1
1	09/28/93	AS	600	10000	52	3	12	<1	147	<1
8	09/29/93	AS	740	10000	13*	1	13*	32	<1*	<1
8	09/29/93	UA	740	10000	13*	2	13*	68	<1*	<1
8	09/29/93	HT	740	10000	13*	3	13*	92	<1*	60
8	09/29/93	SE	740	10000	13*	<1	13*	22	<1*	42
3	10/04/93	UA	800	5000	52*	2	314*	16	78*	12
3	10/04/93	HT	880	5000	52*	5	314*	24	78*	18
3	10/04/93	AS	880	5000	52*	2	314*	14	78*	9
3	10/04/93	SE	880	5000	52*	1	314*	12	78*	<1
9	10/05/93	UA	800	2500	26*	2	326*	20	162*	6
9	10/05/93	HT	880	2500	26*	3	326*	40	162*	22
9	10/05/93	AS	880	2500	26*	2	326*	14	162*	12
9	10/05/93	SE	880	2500	26*	<1	326*	16	162*	6
6	10/06/93	HT	880	10000	52*	13	327*	66	157*	42
6	10/06/93	UA	800	10000	52*	2	327*	14	157*	14
6	10/06/93	SE	880	10000	52*	3	327*	22	157*	10
6	10/06/93	AS	880	10000	52*	6	327*	34	157*	18
8	10/07/93	UA	740	10000	3*	4	177*	29	94*	24
8	10/07/93	HT	740	10000	3*	14	177*	82	94*	56
8	10/07/93	AS	740	10000	3*	8	177*	46	94*	22
8	10/07/93	SE	740	10000	3*	3	177*	30	94*	32
5	10/08/93	UA	740	5000	26*	2	320*	18	154*	16
5	10/08/93	HT	740	5000	26*	13	320*	72	154*	42
5	10/08/93	AS	740	5000	26*	6	320*	38	154*	18
5	10/08/93	SE	740	5000	26*	3	320*	34	154*	16
2	10/11/93	UA	740	2500	0*	0	300*	23	138*	13
2	10/11/93	SE	740	2500	0*	2	300*	13	138*	12
2	10/11/93	HT	740	2500	0*	0	300*	24	138*	24
2	10/11/93	AS	740	2500	0*	0	300*	36	138*	19
4	10/12/93	UA	600	2500	28*	5	301*	40	175*	24
4	10/12/93	HT	600	2500	28*	12	301*	60	175*	41
4	10/12/93	AS	600	2500	28*	8	301*	49	175*	36
4	10/12/93	SE	600	2500	28*	8	301*	62	175*	88
7	10/12/93	UA	600	5000	37*	13	375*	78	162*	40
7	10/12/93	SE	600	5000	37*	25	375*	140	162*	115
7	10/12/93	HT	600	5000	37*	<1	375*	2	162*	64
7	10/12/93	AS	600	5000	37*	7	375*	67	162*	57
1	10/13/93	UA	600	10000	45*	16	257*	96	129*	46
1	10/13/93	HT	600	10000	45*	17	257*	91	129*	78
1	10/13/93	SE	600	10000	45*	32	257*	172	129*	119
1	10/13/93	AS	600	10000	45*	8	257*	74	129*	56
09r	11/11/93	UA	800	2500	48	1	26	34	136	8
09r	11/11/93	SE	880	2500	48	0	26	27	136	2
09r	11/11/93	AS	880	2500	48	<1	26	8	136	8
09r	11/11/93	HT	880	2500	48	0	26	5	136	3
04r	11/12/93	SE	600	2500	50	5	274	40	138	72
02r	11/12/93	SE	740	2500	50	0	274	20	138	14

\* Denotes average value.

**APPENDIX F**  
**Evaluation of Catalyst X**

## APPENDIX F

### Evaluation of Catalyst X

Catalyst X, an experimental catalyst produced by a commercial vendor, was tested during the extended test. This is a novel type of catalyst based on first row transition metal oxides dispersed on a carbonaceous support. The metal oxides produce a large surface area when dispersed over the surface of the pores of the support. This type of catalyst is thought to be capable of totally oxidizing various hydrocarbons at low temperatures. The manufacturer claims moderate success at destroying hydrocarbons including hexane, toluene, butane, trichloroethylene, and tetrachloroethylene.

Table F-1 presents the destruction efficiency data for DCA collected during the extended test. The catalyst initially was operated at a  $5000 \text{ hr}^{-1}$  space velocity and a bed temperature of  $480^{\circ}\text{F}$ . The average conversion during this phase of the test was about 15%. On day 22, the bed temperature was increased to  $570^{\circ}\text{F}$ . Over the following 2 weeks the average conversion increased to about 22%. Additional tests were performed by varying the space velocity and bed temperature. The results are presented in Table F-2. There are two noticeable trends. As the space velocity is decreased, the percent conversion increases and as the bed temperature is increased, the percent conversion increases. Because of limitations in the bench-scale equipment as well as time limitations, we were not able to implement all of the recommendations suggested by the manufacturer for optimizing conversion. Additional tests, varying the space velocity and bed temperature should be conducted to determine optimum oxidation conditions. The effects of humidity on the conversion of DCA also should be addressed.

**TABLE F-1. DCA DESTRUCTION EFFICIENCY USING CATALYST**

Date	Day	Inlet DCA Concentration to Catalysts (ppb)	% Destruction
05/11/94	1	2,808	22.2
05/13/94	3	1,941	15.1
05/17/94	7	1,809	22.6
05/18/94	8	1,393	8.0
05/19/94	9	1,685	11.3
05/23/94	13	1,813	11.7
05/25/94	15	1,815	14.9
05/27/94	17	1,842	13.7
05/31/94	21	1,854	17.5
06/01/94	22	1,565	10.5
06/10/94	31	2,691	18.8
06/12/94	33	2,442	21.5
06/13/94	34	1,865	64.4
06/14/94	35	3,084	21.3
06/15/94	36	1,928	22.3
06/16/94	37	1,305	11.1
06/17/94	38	2,800	27.8
06/19/94	40	1,348	22.9
06/22/94	43	2,424	33.5
06/23/94	44	2,157	72.9
06/28/94	49	1,415	-2.7
06/30/94	50	1,228	-15.5
06/30/94	51	1,423	4.6
07/02/94	53	1,469	10.9
07/04/94	55	2,626	19.9
07/05/94	56	3,827	40.6
07/07/94	58	2,989	96.1

**TABLE F-2. PERCENT CONVERSION OF DCA AT VARIOUS OPERATING CONDITIONS**

Space Velocity (1/hr)	Bed Temperature (F)	% Conversion
2,500	557	52
5,000	567	11
7,500	576	3
500	660	61
2,500	638	75

**APPENDIX G**  
**By-Products from Catalytic Oxidizers**

## APPENDIX G

### BY-PRODUCTS FROM CATALYTIC OXIDIZERS

By-products from the catalytic oxidizers were measured using a Sensidyne™ detector with Sensidyne™ detector tubes. In cases where the exhaust gas was hot, as in the case of the ARI fluidized-bed incinerator, a hot probe was used to allow the gas to cool before entering the detector. To analyze a sample, the detector tube was placed into the ¼-inch Swagelok fitting used to collect the outlet air samples for gas chromatograph analysis. The exhaust gas was analyzed for carbon dioxide, carbon monoxide, hydrochloric acid, chlorine, and phosgene. The results are presented in Table G-1. Generally, the sample was collected and analyzed using one pump stroke. In the case of carbon dioxide, two pump strokes were used. The resulting concentration was then divided in half. If detected at all, carbon dioxide generally fell around the minimum detectable concentration of the tube. Carbon monoxide and phosgene were below the minimum detectable concentration for each of the catalytic oxidizers. The photocatalytic incinerator produced low concentrations of both hydrochloric acid and chlorine.

**TABLE G-1. RESULTS OF TESTS FOR BY-PRODUCTS FROM CATALYTIC INCINERATORS**

Test	UA Catalyst	HT Catalyst	AS Catalyst	SE Catalyst	X Catalyst	KSE Photocatalytic
CO <sub>2</sub>	0.32 %	0.18 %	0.26 %	0.13 %	<0.25 %	<0.25 %
CO	<25 ppm	<25 ppm	<25 ppm	<25 ppm	<25 ppm	<25 ppm
HC1	<0.1 ppm	<1.0 ppm	<0.1 ppm	<1.0 ppm	<1.0 ppm	3.5 ppm
C1	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	<0.5 ppm	0.5 ppm
Phosgene	<0.1 ppm	<0.1 ppm	<0.1 ppm	<0.1 ppm	<0.1 ppm	<0.1 ppm

For a more detailed analysis of by-products, inlet and outlet air samples from the four catalysts (UA, HT, AS, and SE) were collected in canisters and taken to an off-site laboratory for analysis by GC-MS. The results are shown in Table G-2. Only the vinyl chloride level was noticeably higher in the outlet air from the catalyst than in the inlet air. Thus, vinyl chloride is a possible product of incomplete combustion of the heavier organics. However, compared with the approximately 5,000-ppbv total organics in the inlet air, the 39-to 172-ppbv of vinyl chloride in the outlet air is insignificant, especially given the fact that there is up to 48 ppbv of vinyl chloride in the inlet air to begin with.



TABLE G-2. CANISTER SAMPLING RESULTS FROM DOVER AFB STUDY\*

Compound	Ambient Air	Inlet Air	Inlet Air	UA Catalyst	HT Catalyst	AS Catalyst	SE Catalyst	SE Catalyst
1) dichlorodifluoromethane	0.28	n.d.	n.d.	n.d.	n.d.	0.63	n.d.	n.d.
2) methyl chloride	n.d.	22.33	20.25	0.50	1.70	4.64	1.15	2.13
3) 1,2-dichloro-1,1,2,2-tetrafluoroethane	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
4) vinyl chloride	n.d.	16.84	48.07	81.40	171.60	89.99	40.45	39.23
5) 1,3-butadiene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
6) methyl bromide	n.d.	n.d.	n.d.	n.d.	0.04	n.d.	n.d.	n.d.
7) ethyl chloride	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
8) trichlorofluoromethane	0.40	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
9) 1,1-dichloroethene	n.d.	n.d.	n.d.	0.20	n.d.	n.d.	n.d.	n.d.
10) dichloromethane	n.d.	38.55	28.18	0.90	0.20	n.d.	4.93	10.69
11) 3-chloropropene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
12) 1,1,2-trichloro-1,2,2-trifluoroethane	0.35	n.d.	n.d.	11.10	3.00	0.48	55.47	116.25
13) 1,1-dichloroethane	n.d.	n.d.	n.d.	n.d.	0.80	0.38	0.20	0.18
14) cis-1,2-dichloroethene	n.d.	62.46	62.46	6.60	7.30	7.28	2.35	2.24
15) trichloromethane	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
16) 1,2-dichloroethane	n.d.	4596.11	5074.71	321.50	141.10	408.17	70.88	68.64
17) 1,1,1-trichloroethane	0.26	24.52	28.06	1.80	0.80	2.28	0.45	0.46
18) benzene	0.52	28.55	31.60	2.70	13.50	18.79	6.41	6.65
19) carbon tetrachloride	0.25	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
20) 1,2-dichloropropane	n.d.	n.d.	n.d.	n.d.	0.20	n.d.	n.d.	n.d.
21) trichloroethene	n.d.	162.99	182.88	21.80	28.10	24.45	7.83	7.57
22) cis-1,3-dichloropropene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
23) trans-1,3-dichloropropene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
24) 1,1,2-trichloroethane	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
25) toluene	0.38	6.34	n.d.	0.30	0.10	0.11	n.d.	n.d.
26) 1,2-dibromoethane	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
27) tetrachloroethene	0.22	142.50	158.36	24.50	38.70	27.08	10.57	10.35
28) chlorobenzene	0.21	7.44	n.d.	0.30	0.50	0.30	0.23	0.21
29) ethylbenzene	0.17	n.d.	n.d.	n.d.	0.20	n.d.	n.d.	n.d.
30) m+p-xylene	n.d.	n.d.	n.d.	n.d.	0.20	n.d.	n.d.	n.d.
31) styrene	0.29	n.d.	n.d.	0.40	0.20	0.15	n.d.	n.d.
32) 1,1,2,2-tetrachloroethane	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
33) o-xylene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
34) 4-ethyltoluene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
35) 1,3,5-trimethylbenzene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
36) 1,2,4-trimethylbenzene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
37) benzyl chloride	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
38) m-dichlorobenzene	n.d.	6.95	n.d.	0.40	0.30	0.35	0.13	0.12
39) p-dichlorobenzene	n.d.	6.22	n.d.	0.20	0.20	0.24	n.d.	0.10
40) o-dichlorobenzene	n.d.	7.20	n.d.	0.10	0.10	n.d.	n.d.	n.d.
41) 1,2,4-trichlorobenzene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
42) hexachlorobutadiene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. = compound not detected.

\* Concentrations reported in parts per billion by volume (ppbv).

## **APPENDIX H**

### **Mass Balance on Air Stripping Towers**

**TABLE H-1. MASS BALANCE CALCULATIONS FOR PRELIMINARY TEST DATA FOR AIR STRIPPING**

[illegible]

TABLE H-2. MASS BALANCE CALCULATIONS FOR EXTENDED TEST DATA FOR AIR STRIPPING

Day	DCA Conc Inlet Water (mg/l)	DCA Conc in Inlet Air (mg/l)				DCA Conc in Outlet Air (mg/l)				CC Tower				CF Tower			
		CC		CF		CC		CF		Mass DCA Removed From H2O Stream (mg/l)		Mass DCA Gained in Air Stream (mg/l)		Mass DCA Removed From H2O Stream (mg/l)		Mass DCA Gained in Air Stream (mg/l)	
		CC	CF	CC	CF	CC	CF	CC	CF	Stream	% Dis-crepancy	Stream	% Dis-crepancy	Stream	% Dis-crepancy	Stream	% Dis-crepancy
1	1.103	0.050	0.049	0.0E+00	0.0E+00	0.009	0.006	0.006	0.006	79.7	40.9	40.9	48.7	79.8	44.8	43.9	43.9
3	1.143	0.038	0.052	---	---	0.010	0.007	0.007	0.007	83.6	46.9	46.9	43.9	82.6	49.4	40.2	40.2
7	0.935	0.032	0.060	---	---	0.008	0.007	0.007	0.007	68.4	36.2	36.2	47.1	66.3	49.0	26.1	26.1
13	0.954	0.041	0.061	3.9E-05	3.8E-05	0.008	0.006	0.006	0.006	69.1	37.7	37.7	45.5	67.6	45.7	32.4	32.4
15	0.689	0.027	0.049	3.8E-05	3.8E-05	0.009	0.007	0.007	0.007	50.1	38.6	38.6	23.0	48.4	50.3	-3.8	-3.8
17	0.792	0.022	0.053	4.0E-05	4.0E-05	0.008	0.007	0.007	0.007	58.3	37.4	37.4	35.8	55.9	49.0	12.4	12.4
21	0.766	0.028	0.067	6.6E-06	6.6E-06	0.008	0.007	0.007	0.007	55.9	36.1	36.1	35.4	52.9	49.8	5.9	5.9
22	0.649	0.030	0.051	1.5E-05	1.5E-05	0.007	0.006	0.006	0.006	46.9	33.0	33.0	29.5	45.3	45.6	-0.8	-0.8
31	1.312	0.055	0.083	1.9E-05	1.9E-05	0.013	0.010	0.010	0.010	95.2	60.0	60.0	36.9	93.0	71.2	23.4	23.4
33	1.188	0.043	0.064	1.0E-05	1.0E-05	0.012	0.009	0.009	0.009	86.7	52.5	52.5	39.4	85.1	61.6	27.6	27.6
34	0.781	0.028	0.038	4.5E-05	4.5E-05	0.009	0.006	0.006	0.006	57.0	38.7	38.7	32.1	56.2	45.0	19.9	19.9
36	0.765	0.030	0.044	1.3E-05	1.3E-05	0.009	0.007	0.007	0.007	55.7	39.3	39.3	29.4	54.6	46.4	15.0	15.0
38	1.193	0.045	0.070	4.1E-05	4.1E-05	0.013	0.010	0.010	0.010	86.9	57.3	57.3	34.1	85.0	67.0	21.2	21.2
40	0.866	0.030	0.048	1.6E-05	1.6E-05	0.009	0.008	0.008	0.008	63.3	41.0	41.0	35.2	62.0	54.4	12.2	12.2
43	1.097	0.031	0.053	6.3E-05	6.3E-05	0.012	0.009	0.009	0.009	80.7	52.9	52.9	34.4	79.0	63.4	19.7	19.7
44	1.671	0.056	0.087	0.0E+00	0.0E+00	0.013	0.010	0.010	0.010	122.3	59.4	59.4	51.4	119.9	70.9	40.9	40.9
49	1.0225	0.028	0.044	1.6E-05	1.6E-05	0.005	0.004	0.004	0.004	75.3	21.7	21.7	71.1	74.1	31.2	57.9	57.9
51	0.632	0.018	0.024	4.0E-05	4.0E-05	0.003	0.002	0.002	0.002	46.5	15.6	15.6	66.5	46.0	11.0	76.1	76.1
53	0.733	---	0.027	5.0E-05	5.0E-05	0.007	0.007	0.007	0.007	55.5	32.7	32.7	41.0	53.5	48.3	9.7	9.7
55	1.56	0.080	0.113	1.4E-04	1.4E-04	0.005	0.006	0.006	0.006	112.0	24.1	24.1	78.5	109.5	43.4	60.4	60.4
63	0.8725	0.023	0.037	9.3E-06	9.2E-06	0.009	0.006	0.006	0.006	64.3	40.1	40.1	37.7	63.2	40.7	35.6	35.6
63a	1.152	0.025	0.029	9.3E-06	9.2E-06	0.009	0.007	0.007	0.007	85.3	41.8	41.8	51.0	85.0	48.5	42.9	42.9
64	0.892	0.027	0.034	7.0E-05	7.0E-05	0.009	0.007	0.007	0.007	65.5	39.5	39.5	39.7	65.0	51.9	20.2	20.2

## **APPENDIX I**

### **Sample Mass Transfer Coefficient Calculations**

## APPENDIX I

### Sample Mass Transfer Coefficient Calculations

The equations used to calculate the overall mass transfer coefficient are presented in the following step-by-step examples using data collected from Day 33 of the extended test (Tables H-1 and H-2).

1. Calculate the stripping factor

$$S = \frac{H}{P} \left[ \frac{G}{L} \right] \quad (1)$$

where H is the Henry's Law constant (atm), G is the gas molar flow rate (kmol/s), L is the liquid molar flow rate (kmol/s), and P is assumed to be 1 atm. (Note:  $H = 0.055$  dimensionless = 73.1 atm.)

CCAS:

$$S = \frac{73.1}{1} \left[ \frac{2.98 \times 10^{-3}}{7.01 \times 10^{-2}} \right] = 3.11 \quad (2)$$

CFAS:

$$S = \frac{73.1}{1} \left[ \frac{4.62 \times 10^{-3}}{7.01 \times 10^{-2}} \right] = 4.82 \quad (3)$$

2. Calculate the number of transfer units.

$$NTU = \left[ \frac{S}{S-1} \right] \ln \left[ \frac{(C_{L,in} - C_{G,in}/H) (S-1)}{(C_{L,out} - C_{G,out}/H) S} + \left[ \frac{1}{S} \right] \right] \quad (4)$$

where  $C_{L,in}$  is the influent water concentration (kg/m<sup>3</sup>),  $C_{L,out}$  is the effluent water concentration, and  $C_{G,in}$  is the influent air concentration (kg/m<sup>3</sup>).  $C_{G,in}$  is very small and therefore is assumed to be negligible.

CCAS:

$$NTU = \left[ \frac{3.11}{3.11-1} \right] \ln \left[ \frac{(1148-0/74.1) (3.11-1)}{(43-0/74.1) 3.11} + \frac{1}{3.11} \right] = 4.29 \quad (5)$$

CFAS:

$$NTU = \left[ \frac{4.82}{4.82-1} \right] \ln \left[ \frac{(1148-0/74.1)}{(64-0/74.1)} \frac{(4.82-1)}{4.82} + \frac{1}{4.82} \right] = 3.37 \quad (6)$$

3. Calculate the height of a transfer unit (HTU).

$$HTU = \frac{Z}{NTU} \quad (7)$$

where Z is the packed height (m).

CCAS:

$$HTU = \frac{5.18}{4.29} = 1.21 \text{ m} \quad (8)$$

CFAS:

$$HTU = \frac{5.18}{3.37} = 1.52 \text{ m} \quad (9)$$

4. Calculate the overall mass transfer coefficient.

$$K_L a = \frac{L_m}{P_L(HTU)} \quad (10)$$

where  $L_m$  is the water mass loading ( $\text{kg/m}^2\text{s}$ ) and  $P_L$  is the density of water ( $\text{kg/m}^3$ ).

CCAS:

$$K_L a = \frac{7.69}{1000(1.21)} = 6.35 \times 10^{-3} \text{ s}^{-1} \quad (11)$$

CFAS:

$$K_L a = \frac{7.13}{1000(1.52)} = 4.69 \times 10^{-3} \text{ s}^{-1} \quad (12)$$

Tables I-1 and I-2 present the overall mass transfer coefficients for the CCAS and CFAS towers for the preliminary and extended tests, respectively.

TABLE I-1. MASS TRANSFER COEFFICIENTS — PRELIMINARY TEST SET

Test	Air Flow Rate (scfm)	Water Flow Rate (gal/min)	Experimental $K_L a$ (1/s)	
			CC	CF
1	175	50	5.65E-03	3.30E-03
2	100	20	4.10E-03	2.00E-03
2	100	20	4.72E-03	2.80E-03
2	100	20	4.42E-03	2.38E-03
3	250	35	7.62E-03	5.19E-03
4	100	35	3.65E-03	2.99E-03
5	250	50	8.05E-03	4.46E-03
6	175	20	7.37E-03	3.60E-03
6	175	20	6.87E-03	4.23E-03
7	250	20	6.91E-03	3.49E-03
8	175	35	7.59E-03	4.38E-03
9	100	50	3.91E-03	1.83E-03
E1	295	20	8.32E-03	4.13E-03
E2	295	20	7.42E-03	4.05E-03
10	175	50	6.44E-03	3.80E-03
11	100	20	5.56E-03	2.25E-03
12	250	35	9.98E-03	4.67E-03
13	100	35	4.22E-03	2.52E-03
14	250	50	8.44E-03	5.41E-03
15	175	20	8.31E-03	3.52E-03
16	250	20	8.52E-03	4.32E-03
17	175	35	7.59E-03	3.69E-03
18	100	50	4.17E-03	2.02E-03
18	100	50	3.70E-03	1.70E-03
19	175	50	6.12E-03	3.24E-03
20	100	20	5.00E-03	1.87E-03
21	250	35	1.14E-02	3.78E-03
22	100	35	3.51E-03	2.29E-03
22	100	35	4.49E-03	2.19E-03
23	250	50	6.95E-03	4.98E-03
24	175	20	7.84E-03	3.01E-03
25	250	20	8.62E-03	3.14E-03
25	250	20	8.42E-03	3.55E-03
26	175	35	6.72E-03	3.58E-03
27	100	50	3.50E-03	1.93E-03
1r	175	50	7.56E-03	3.53E-03
2r	100	20	4.89E-03	1.81E-03
3r	250	35	9.76E-03	4.25E-03
4r	100	35	2.88E-03	1.17E-03
5r	250	50	1.05E-02	4.88E-03
6r	175	20	7.27E-03	3.02E-03
7r	250	20	7.20E-03	3.47E-03
8r	175	35	7.36E-03	2.84E-03
9r	100	50	2.17E-03	5.67E-04
X1	290	20	8.07E-03	3.81E-03
X2	300	10	4.36E-03	2.48E-03



TABLE I-2. MASS TRANSFER COEFFICIENTS — EXTENDED TEST SET

Day	Air Flow Rate (scfm)	Water Flow Rate (gal/min)		Experimental $K_L a$ (1/s)	
				CC	CF
1	160	250	20	5.95E-03	5.01E-03
2	160	251	20	5.68E-03	4.58E-03
3	160	250	20	6.55E-03	4.95E-03
5	164	250	20	5.80E-03	4.22E-03
7	162	250	20	6.49E-03	4.39E-03
9	160	249	20	6.57E-03	4.42E-03
13	160	250	21	6.46E-03	4.65E-03
14	160	250	20	6.18E-03	4.29E-03
15	160	250	20	6.27E-03	4.21E-03
17	160	250	20	6.96E-03	4.29E-03
21	160	250	20	6.47E-03	3.86E-03
22	160	250	20	5.95E-03	4.06E-03
31	160	250	20	6.15E-03	4.42E-03
33	160	250	20	6.45E-03	4.69E-03
34	160	250	20	6.47E-03	4.87E-03
36	160	250	20	6.35E-03	4.59E-03
38	160	250	20	6.34E-03	4.54E-03
40	160	250	20	6.59E-03	4.68E-03
43	160	250	20	6.99E-03	4.88E-03
44	160	250	20	6.66E-03	4.78E-03
49	160	250	20	7.03E-03	5.02E-03
51	160	250	20	6.92E-03	5.27E-03
53	160	250	20	—	5.38E-03
55	160	250	20	5.69E-03	4.18E-03
58	160	250	20	6.47E-03	4.75E-03
63	160	250	20	7.16E-03	5.11E-03
63a	160	250	20	7.58E-03	6.01E-03
64	160	250	20	6.87E-03	5.30E-03
64a	300	300	20	8.91E-03	5.79E-03

## **APPENDIX J**

### **Spreadsheet for Scale-up Calculations for Air Stripping**

TABLE J-1. SCALE-UP SPREADSHEET FOR CCAS TOWER DESIGN

CC Tower			
Input	Intermediate	Output	
Air Temp=	288.7 K		
Air Density=	0.076 lb/cu ft		
Water Density=	62.43 lb/cu ft		
Packing Factor=	55		
Kinematic Viscosity=	0.001482 cp		
H=	0.055	72.4 atm	
L=	180 gpm		
Cg1=	0 ppm	Gm=	
Cl2=	1 ppm		Diameter=
Cl1=	0.05 ppm		Packed Area=
G/L=	60		
Lv=	13 gpm/sq ft	Lm=	108.5 lb/sq ft/min
Kla=	0.00641 1/s	Gv=	104.3 scfm/sq ft
		Eckert Plot, X=	0.478
		Eckert Plot, Y=	0.106
		Stripping Factor, S=	3.28
		NTU=	3.82
		HTU=	4.52 ft
			Efficiency, E=
			95 %
Packing Pressure Drop=	2 in water		Tower Height, Z=
System Pressure Drop=	1 in water	Total Pressure Drop=	17.2 ft
		0.108 psi	Blower HP=
			0.85 hp



## **APPENDIX K**

### **Pretreatment Chemicals for Groundwater Remediation**

## APPENDIX K

### PRETREATMENT OF GROUNDWATER

Pretreatment of the groundwater is usually needed for two reasons:

- To prevent iron or other elements, such as calcium, magnesium, etc., from precipitating out of the water onto the packing
- To control microbial growth on the packing.

Common pretreatment methods for groundwater often show conflicting results. For example, a common chelating agent, sodium citrate was used during the preliminary test to sequester iron. Although, iron precipitation was prevented, the citrate served as a nutrient source for microbial growth. Even in the absence of an introduced carbon source, microbial growth can occur. In a previous study at Wurtsmith AFB (Gross and TerMaath, 1985), the researchers found that microbial growth was causing the stripping tower to plug up every few months. At Wurtsmith, the microbes were actually believed to be feeding on the trichloroethylene contaminant in the groundwater.

The other problem is that common biocides, such as hypochlorite, may be undesirable for use in air stripping if the final effluent is being discharged to a natural water body. One way of addressing the discharge problem is to recirculate the biocide through the towers and into a holding tank in a closed loop. Once the cleaning is over, the contents of the holding tank can either be treated or discharged to an on-site wastewater treatment plant or municipal sewer (after obtaining required permits).

A more benign approach was used during the extended test when a hot water recirculation system was used. This approach was very effective in cleaning the towers of microbial growth. After a brief cooling period, the cooled water could be safely discharged to a stream. However, these are periodic remedies that require the system to be shut down for some time. Special additives that can be used for continuous pretreatment of the groundwater before air stripping are commercially available, and may be worth a try. Although somewhat expensive, these additives can be added to the water on a continuous basis. The following information in this appendix is the recommendation provided by one commercial supplier and is reproduced here with their permission.

## Windham Environmental Corp.

RR#1 Box 27, Newfane, VT 05345

Phone: 802-365-7198

Fax: 365-4652

March 15, 1994

Arun Gavaskar  
Battelle  
505 King Ave.  
Columbus, OH 43220

Dear Arun,

Thank you for taking the time to chat with me last Friday regarding your iron / bio-fouling problems. I apologize for the delay in getting this information out to you, but I wanted to make several cost effective options available to you.

### Option #1

The use of our FeREMEDE PLUS would be my first choice in this situation, it is a combination of FeREMEDE (our top sequesterant), and our B126 Microbiocide. When used for a short period (such as two weeks), your bug problem should be reduced enough to start using straight FeREMEDE. Due to the organic nature of the sequesterant you are presently using, we feel this is most likely your primary nutrient source for the bug growth. FeREMEDE is non nutrient rich and by properly tying up the metals at hand and removing a major nutrient source, the use of a constant dose of biocide may not be required. If for some inexplicable reason bugs should reappear try option #2.

### Option #2

Due to the Expense of using FeREMEDE PLUS on an prolonged basis it may be more cost effective to use our FeREMEDE product on a constant flow basis and then periodically shock the bugs with high doses of B126 (100 ppm, 2-3 times per week for an hour). If permitting becomes an issue (Usually only on potable systems), see option #3.

### Option #3

Our FeREMEDE 200 is a polyphosphate based sequesterant. It is NSF approved and may also be obtained in an FDA grade if required. Although it is not as effective as FeREMEDE, for applications such as ground water injection and municipal water discharge it is more widely accepted. This option would still have to be used in conjunction with our B126 biocide.

Note: Although B126 will readily break down upon release and was developed with surface water discharges in mind, it may have to be diluted somewhat to be discharged into prime or potable water sources.

We are manufacturers representatives specializing in environmental process equipment, offering high quality equipment plus the technical expertise to assure appropriate application of our product lines.

Remede Inc. manufactures the FeREMEDE™ line of chemicals to control deposits in remediation equipment. These patented products are mixtures of chelating agents, dispersants, biocides and other proprietary ingredients. They are the only products specifically designed to control fouling encountered in remedial treatment equipment. Many chemical deposit control agents actually compound maintenance problems: Common chelating agents often act as a nutrients source for bio-growth, while our chelating constituents have been chosen not only for their excellent sequestering abilities in a variety of water chemistries, but also because they are of low nutrient value. Common biocides tend to oxidize iron and manganese out of solution, while our biocide is non-oxidizing and thus, while highly effective, will not promote inorganic precipitation. All product constituents were chosen with surface water discharge limits in mind.

In addition to these chemical deposit control agents, we provide associated equipment and services. Our equipment offering includes chemical feed pumps, filtration equipment and related process equipment.

Please feel free to contact me with any further questions regarding this and other products we offer or if you would like me to send your State case officer our permitting package, please call. We look forward to working with you!

Best Regards,

A handwritten signature in cursive script, appearing to read "Chris Winner".

Chris Winner  
Technical Sales  
Windham Environmental Corporation



# REMEDE

Products, Inc.

## FeREMEDE® Deposit Control Agents

### Product Descriptions

1. FeREMEDE Deposit Control Agent

FeREMEDE is a concentrated blend of chelants, sequestering agents and polymers specifically designed to prevent the precipitation and deposition of metal oxides and hardness salts in groundwater remediation systems using air-stripping towers and trays.

2. FeREMEDE-200 Deposit Control Agent

FeREMEDE-200 is a concentrated sequestering agent designed to prevent the precipitation and deposition of metal oxides and hardness salts in air-stripping towers and trays. Although not as effective as FeREMEDE, the product can be used in units where the system water is discharged to a potable water source.

3. FeREMEDE-PLUS Deposit Control Agent

FeREMEDE-PLUS is a concentrated blend of chelants, sequestering agents and dispersants specifically designed to prevent the precipitation of metal oxides and hardness salts and the deposition of organic-bound contaminants.

4. B-126 Microbiocide

B-126 is a concentrated, non-oxidizing microbiocide that provides broad-spectrum control of bacteria in air-stripping towers and trays. The product is particularly effective in controlling the growth of iron and sulfate-reducing bacteria, which often result in restricted water flows in groundwater remediation equipment.

5. Tower Cleaner-C Microbiocide

Tower Cleaner-C is a concentrated, oxidizing microbiocide that provides broad-spectrum control of a wide variety of bacteria, including iron and sulfate-reducing species, in air-stripping towers and trays. Although again, not as effective as our B-126, the product can be used in units where the system water is discharged to a potable water source.

6. Foamtrol-100 Antifoam

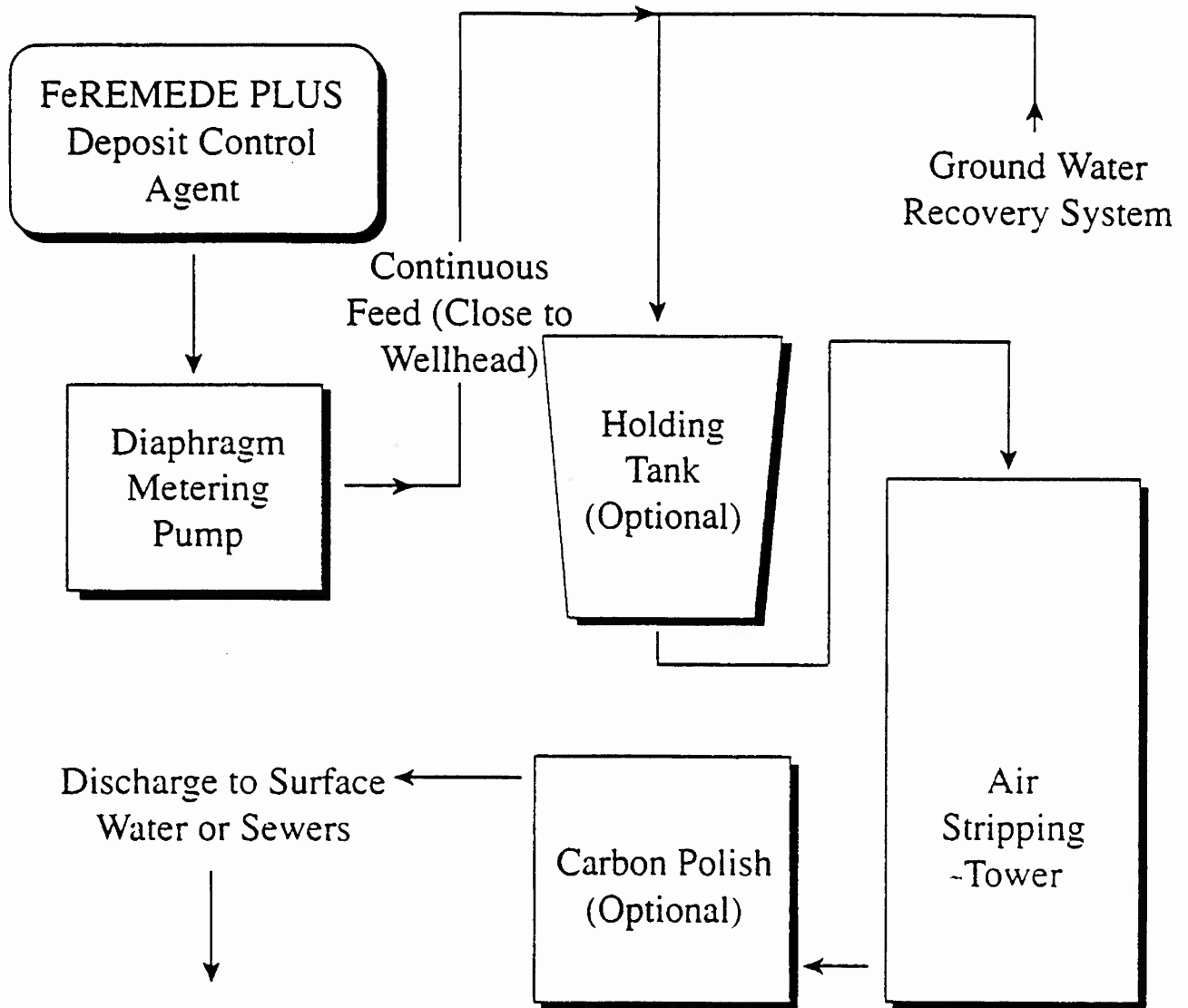
Foamtrol-100 is a concentrated, silica-based product designed to eliminate foaming problems in air-stripping towers and trays. As the product is effective in both alkaline and acidic pH ranges, Foamtrol-100 can be used to control foam in virtually all air-stripping applications.

### Comments:

More detailed information concerning our treatments can be obtained by referring to the individual Product and Material Safety Data Sheets or by contacting our office directly.

# FeREMEDE® PLUS

## Product Application Guidelines



### Options and Accessories

- Engineering design, specification and installation services
- Operation and maintenance packages
- Pump controls - flow sensor/switches, variable controllers and pc interfaces
- Test kits
- Heat tracing for freeze protection
- Explosion-proof accessories

FeREMEDE is a trademark of REMEDE PRODUCTS, Inc.

**APPENDIX L**

**FIELD OPERATIONS MANUAL (CDRL A009)  
FOR CROSSFLOW AIR STRIPPING  
WITH CATALYTIC OXIDATION**

**Task 1, Contract No. F08635-90-C-0064**

**to**

**Major Mark Smith, Technical Project Officer  
Environics Directorate  
Armstrong Laboratory  
AL/EQW  
139 Barnes Drive, Suite 2  
Tyndall AFB, FL 32403-5323**

**from**

**B.C. Kim (Principal Investigator)  
A. R. Gavaskar  
S. K. Ong  
S. H. Rosansky  
C. A. Cummings  
C. L. Criner  
A. J. Pollack  
E. H. Drecsher**

**BATTELLE  
505 King Avenue  
Columbus, OH 43201-2693**

**September 30, 1994**

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\* Provided in separate binders.

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## **SECTION I SYSTEM INSTALLATION**

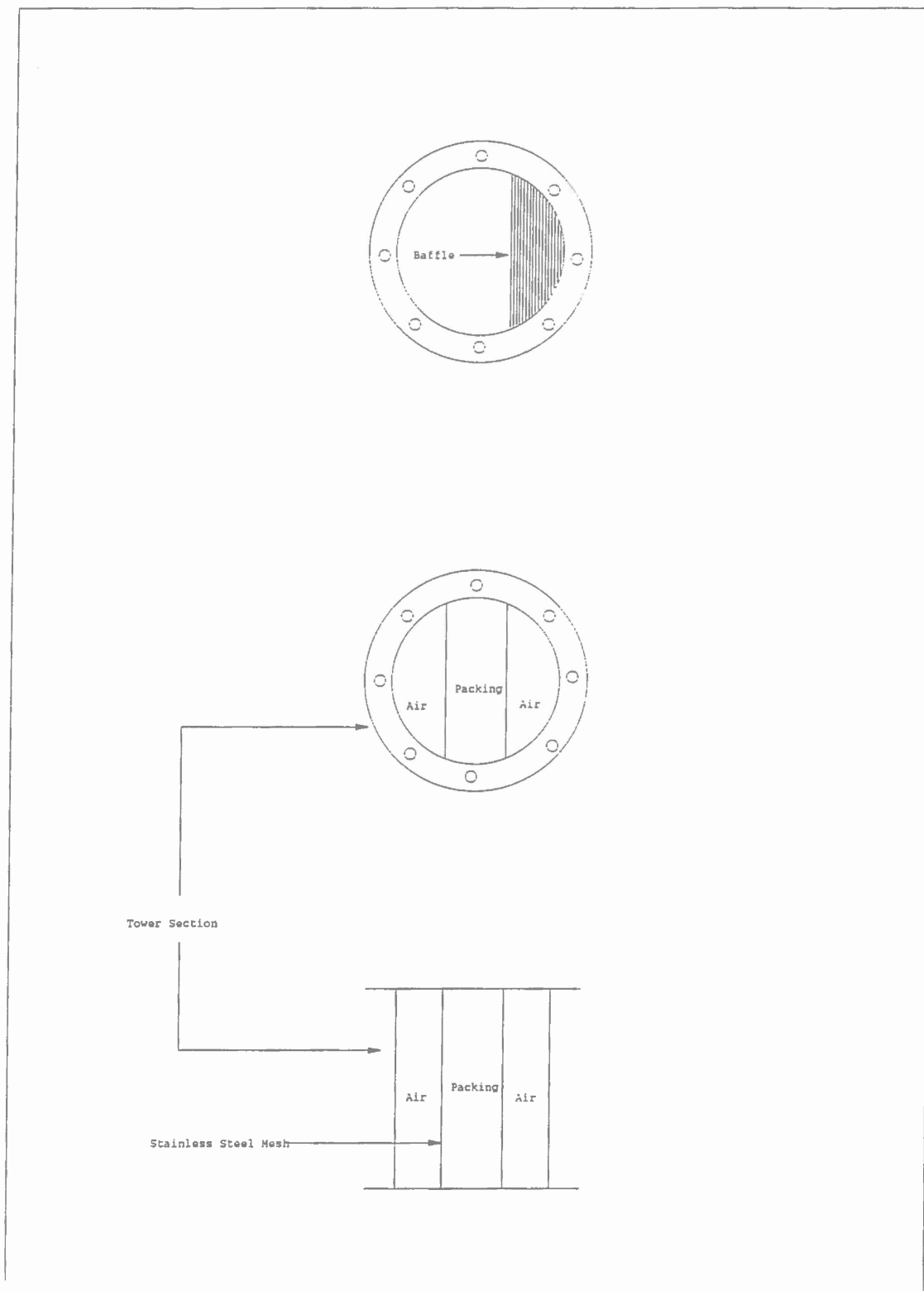
### **A. EQUIPMENT SETUP**

Equipment setup involves installation of the extraction wells, tower assembly, waterline plumbing, air line plumbing, electrical wiring, and installation of the fixed-bed catalysts. Refer to Attachment I for a list of the major equipment. This manual does not cover the instructions necessary for installing the extraction wells.

#### **1. Stripping Tower Installation Instructions**

The air-stripping system includes both countercurrent and crossflow towers. The countercurrent tower is 18 inches in diameter. It consists of a base, two flanged midsections (each approximately 100 inches long), and a flanged top section. The crossflow tower is 24 inches in diameter. It consists of a base, 8 flanged midsections (2 of which are 34 inches long, 6 of which are 24 inches long), and a flanged top section. The bottom section of each tower is mounted to the floor of the trailer. Refer to Attachment II for countercurrent air stripper (CCAS) and crossflow air stripper (CFAS) design blueprints.

The midsections of each tower need to be bolted together. Each section will use 8 bolts. A baffle must be placed between each of the crossflow tower sections. The baffles must be placed on alternating sides of each section to create the crossflow airstream. Check that the baffle is placed so that it completely covers one of the two sides of the tower designated for airflow (see Figure L-1). Place a 1/8-inch neoprene gasket where two metal faces will contact (e.g., between tower sections or



**Figure 1. Cross Sections of Baffle and Tower Sections.**

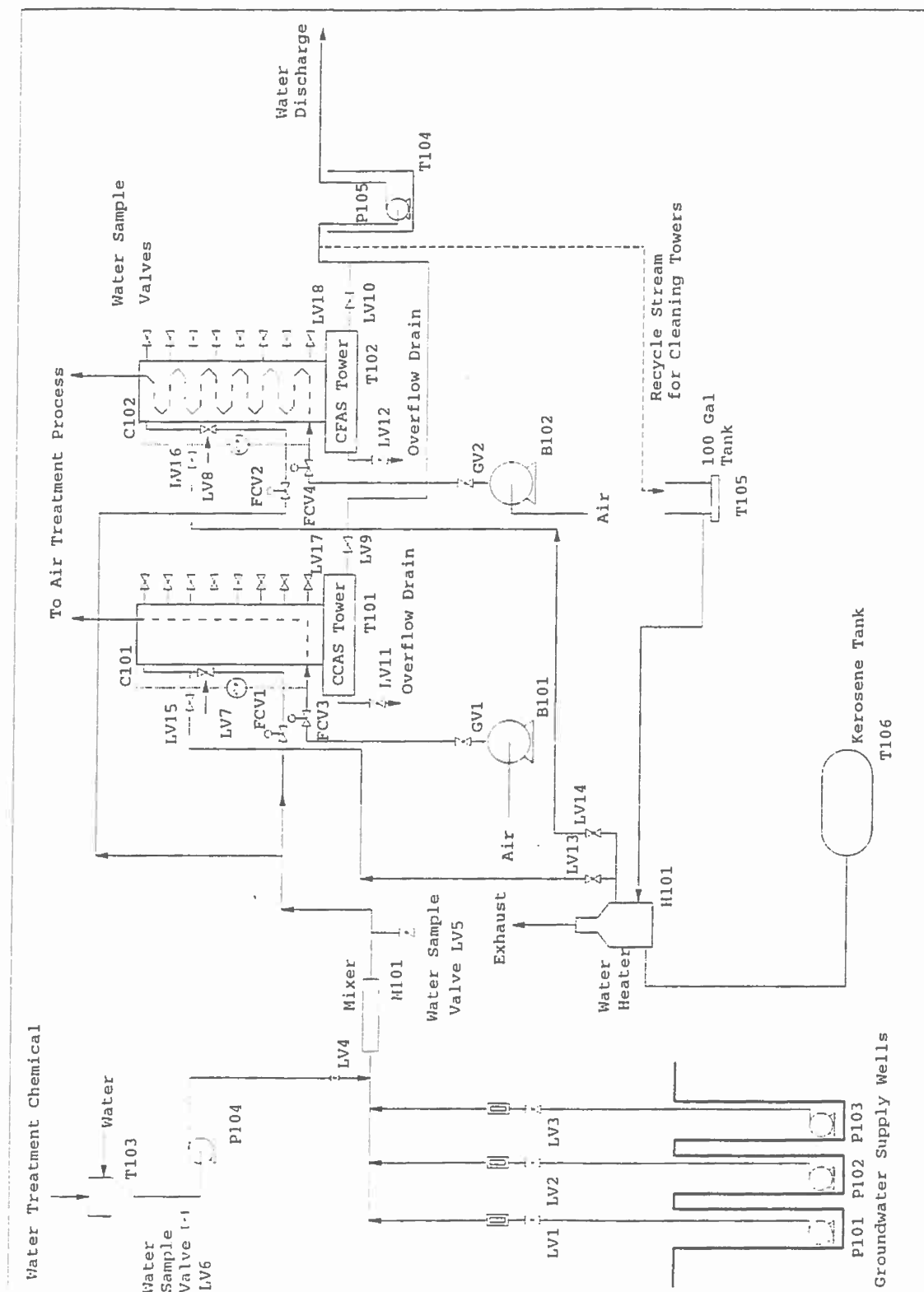
baffle and tower sections). The gasket will prevent leakage out of the tower. Verify that the sampling valves on the sides of the sections are lined up with respect to each other.

After assembling the tower section lift the towers through the roof of the trailer with a crane. Place a baffle on the base of the crossflow tower, being sure that it is aligned in the proper position. Lower the towers onto the base sections and secure with flange bolts. After the towers have been mounted, pour the packing (1-inch polypropylene pall rings) through the opening at the top of each tower. Take care when pouring packing into the crossflow tower to prevent the packing from entering the areas designed for airflow. Place the top sections on the towers (include baffle on crossflow tower). Secure with flange bolts. After the towers have been installed, check to ensure that they are level. If they are not, adjust the leveling nuts at the base of each tower.

## **2. Water Piping Installation**

Figure L-2 illustrates the water piping arrangement. Use the 2-inch schedule 80 pipe that is supplied to plumb the extraction wells to the mixing manifold. The mixing manifold consists of three rotameters with 2-inch fittings, three 2-inch polyvinyl chloride (PVC) ball valves (LV1, LV2, LV3), a stainless steel Nupro™ valve (LV4), a sample valve (LV5), and a stainless steel mixing pipe (M101). The manifold combines the output from the extraction wells, mixes in the water treatment chemical, and splits the resulting stream into two. The manifold is supported by an aluminum stand, which must be assembled. Use 2-inch pipe hangers to support the manifold on the assembled stand. If a water treatment chemical is to be added, it will feed into the mixing manifold (prior to the mixer) through the ¼-inch stainless steel valve (LV4). The water treatment chemical is fed from a tank





(T103) located inside the trailer. A metering pump (P104) controls the rate of addition. Samples can be withdrawn from the water treatment chemical tank through valve LV6.

Use 2-inch PVC to plumb the two exiting streams from the mixing manifold to the flow meter and control valve assembly associated with each tower (FCV1, FCV2). Note that the mass flowmeter must be plumbed with 1 ¼ inch diameter pipe for approximately 2 feet on either side of its inlet and outlet ports. Use 2-inch PVC to plumb from the flow control valves (FCV1, FCV2) to valves LV7 and LV8 on the countercurrent and crossflow towers. Use lengths of aluminum pipe and galvanized fittings to plumb from LV7 and LV8 to the tops of each tower.

Plumb a 3-inch-diameter ball valve (LV9, LV10) to the base of each tower (T101, T102). Plumb a length of 3-inch high-temperature suction hose downstream of the valve using combination hose nipples. Place the opposite ends of the hoses into the surge tank (T104). Place the submersible discharge pump (P105) inside the tank. Plumb the pump outlet using 2-inch-diameter PVC pipe.

The air-stripping setup includes a system for periodically cleaning the towers. This system includes a water heater (H101) and a surge tank (T105). Plumb the water heater to the towers with two lengths of 2-inch high-temperature suction hose and four 2-inch ball valves (LV13, LV14, LV15, LV16). Hard plumb the tank to the water heater using 2-inch galvanized fittings. When cleaning the towers, place the 3-inch water discharge hoses, located at the base of the towers, into the 100 gal surge tank.

### 3. Air Piping Installation

Air is supplied to the process using two blowers (B101, B102). See Figure L-2. Plumb the blowers to the mass flowmeters and flow control valves (FCV3, FCV4) using 6-inch-diameter schedule 80 PVC pipes. Place a 6-inch gate valve (GV1, GV2) at the outlet of each blower to provide additional flow control. Use 6-inch PVC to plumb the control valves to the towers.

The exiting airstream from each tower is piped down alongside the tower through 6-inch-diameter PVC pipes. Refer to Figure L-3. Raise these pipes into place with a crane. Secure them to the top of the towers using  $1\frac{5}{16}$ -inch flange bolts. The two airstreams are combined in an 8-inch-diameter, U-shaped piece of PVC pipe. Assemble the aluminum stand needed to support this piece. Place a water drainage valve (LV17) at the base of this piece to allow for condensate drainage. The combined airstream exits the U-piece in three separate streams. Attach a Y-shaped piece of aluminum duct to the 8-inch outlet of the U. Use a 3-inch-diameter flexible hose to connect the 3-inch-diameter male end of the Y to the inlet side (lower fitting) of the knockout drum (K101). Use another 3-inch-diameter hose to connect the knockout drum and the photocatalytic incinerator (R101). The other end of the Y-piece is left open.

The fixed-bed reactors are hard plumbed inside the trailer. Plumb the 1  $\frac{1}{4}$ -inch-diameter PVC inlet line to the 1  $\frac{1}{4}$ -inch fitting at the top of the U-piece. Connect the exhaust line from the catalyst beds to a 1  $\frac{1}{4}$ -inch-diameter galvanized stack pipe. The stack should be mounted to the crossflow air pipe situated on the outside of the trailer. No additional plumbing is required other than that needed to install the catalysts (see Section L.A.5).

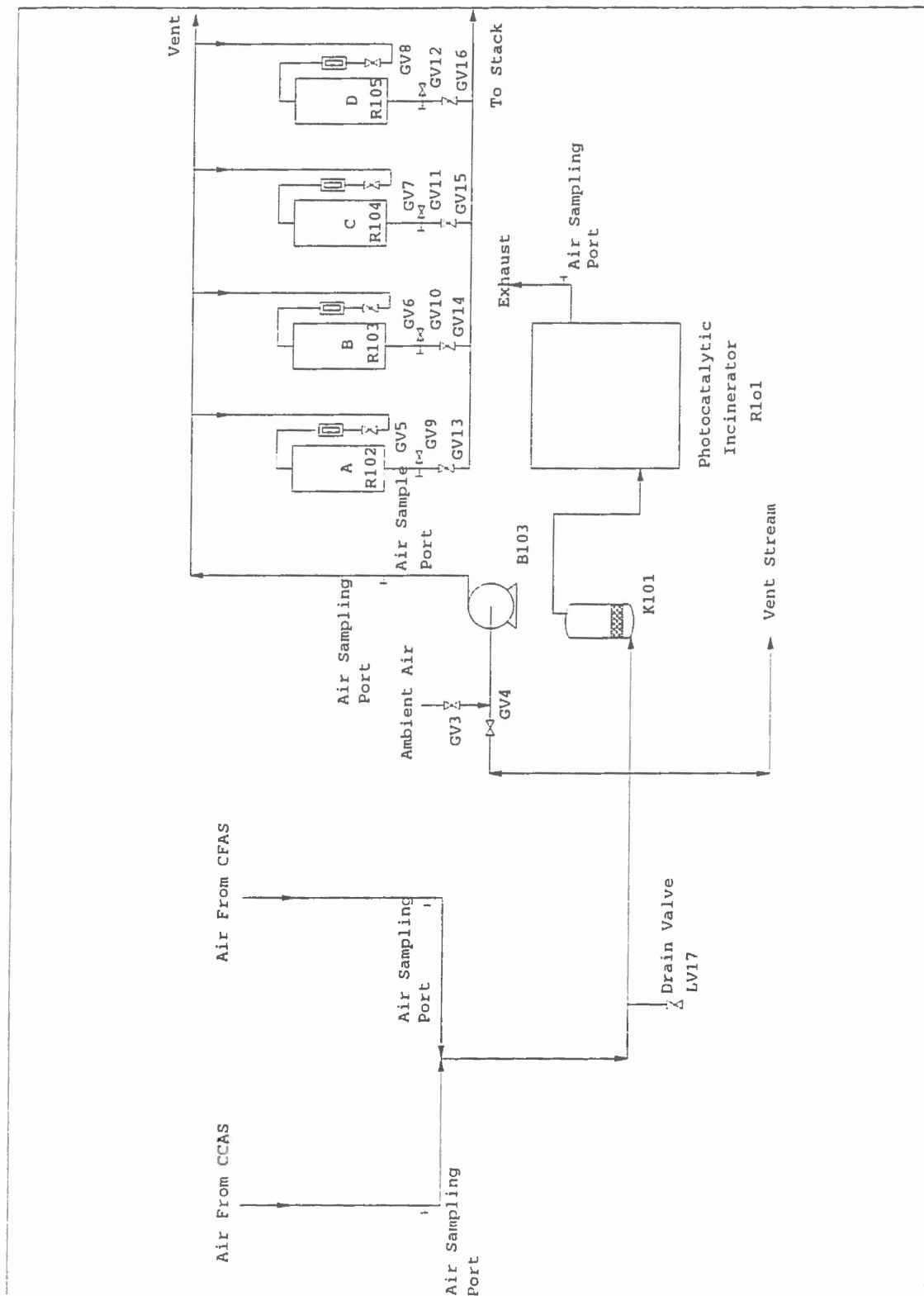


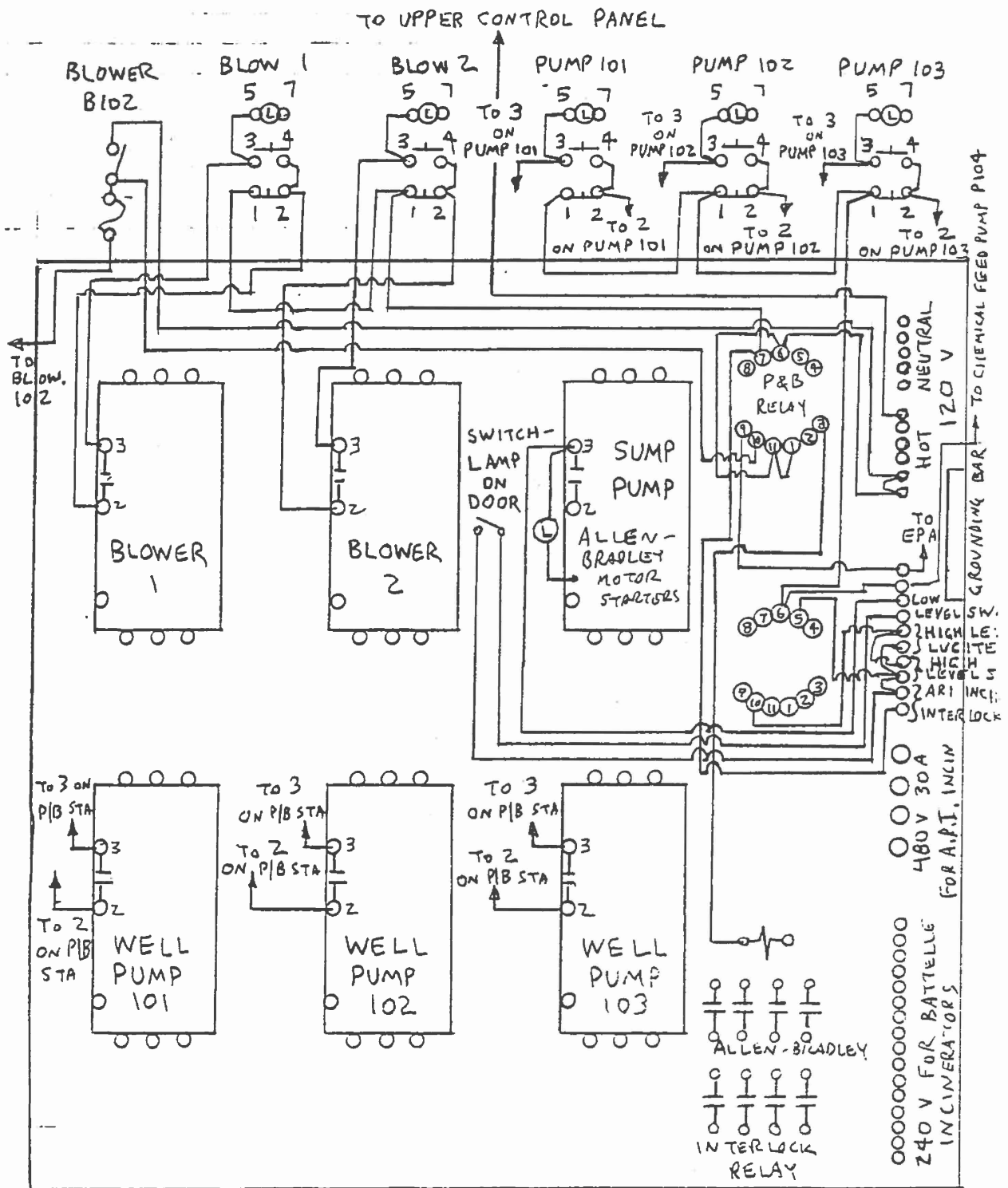
Figure L-3. Air Treatment Process.

#### 4. Electrical Wiring Installation Instructions

a. **AC Wiring.** The blowers (B101, B102), well pumps (P101, P102, P103), submersible pump (P105), and water heater (H101) must be wired into the lower control panel located inside the trailer (see Figure L-2). Each piece of equipment requires a 480-volt, three-phase circuit. Twelve American wire gauge (AWG), three-conductor plus ground-type UF insulation is used to wire these pieces of equipment. Refer to Figure L-4 for the appropriate wire location. After wiring, check rotation. Reverse two wires if rotation is incorrect.

The photocatalytic incinerator (R101) requires one 480-volt, three-phase circuit, one 240 volt single-phase circuit, and four 120-volt circuits. The three-phase circuit is used for the incinerator blower. It requires 12 AWG, three-conductor plus ground, and is wired to the contacts of one of the well pumps in the lower control panel. The 240-volt single-phase circuit controls the operation of the incinerator preheater. It is wired into the 35 amp 2 pole breaker. It requires 10 AWG, three conductor plus ground wire. The four 120-volt circuits, used to control the UV lamps, require 12 AWG, 3-conductor plus ground and are wired to the four 20 amp breakers. Additional wiring information can be found in the Installation Instructions of the KSE Operating Manual, Attachment III. All five breakers are located in a box that should be placed outside of the trailer. The breakers in the box are wired to a main disconnect using 6 AWG wire. The disconnect should be located next to the incinerator. The disconnect is wired to the 15-KVA transformer located inside the trailer.

b. **DC Wiring.** The mass flowmeters and control valves may need to be wired with the 24-volt DC wire supplied from the upper control panel. Connect appropriate wire to device.



LOWER 24-INCH SQ. CONTROL PANEL  
120 V. HOT WIRING

Figure 4. Lower 24-Inch-Square Control Panel (120-V Hot Wiring).

c. **Interlocks.** The following interlocks have been provided to protect process equipment and to avoid untreated water and air.

- The groundwater feed pumps and the water treatment chemical feed pump will not operate if the discharge pump is switched off.
- The power supply to the heaters on the Battelle-built catalytic incinerators (R102, R103, R104, R105) will shut down in the event of the failure of the blower (B103) to these units. Refer to Figure L-3.
- Water carryover to piping upstream of the KSE incinerator will shut down the well pumps (P101, P102, P103) and water treatment pump (P104). Refer to Figure L-2.

## **5. Fixed-Bed Catalyst Installation Instructions**

The following applies to each of the four fixed-bed incinerators. Refer to Figure L-3. Remove the four ¾-inch bolts at the top of the catalyst bed. Disconnect the ¼-inch fitting at the top of the bed. Disconnect the two thermocouple probes. Gently raise the bed out. Unscrew the two small screws that attach the bed (cylindrical canister) to the supporting rod. Place the desired quantity of catalyst into the bed. Pellets or monolithic cylinders can be used. Reattach the supporting rod. Wrap the lowest part of the bed with a ⅛- to ¼-inch piece of Fibrefax™ insulation. Use a small piece of tape to hold the Fibrefax™ in place. The Fibrefax™ will make a seal between the catalyst bed and the incinerator walls. Gently lower the bed into the incinerator. Replace all bolts and fittings.

## SECTION II SYSTEM STARTUP

### A. AIR STRIPPING TOWERS

Check to see that all valves are in the correct position for operating the air stripping system. Valves LV7, LV8, LV9, LV10, GV1, GV2 (on Figure L-2), and GV3 (on Figure L-3) should be wide open. If a water treatment chemical is being added to the process stream, LV4 (on Figure L-3) should also be wide open. Valves LV1, LV2, and LV3 must be at least partially open. Adjust the position of these valves so that the water control valves can maintain a constant value. The diaphragm valves on the mass flow controllers cannot maintain low flow rates (10 to 20 gpm) when large backpressures are present. Leave valve GV4 (on Figure L-3) closed until the catalysts are heated to their appropriate temperatures (see Section II.B). Open valves LV5 and LV6 (Figure L-2) only when collecting water samples. Open valves LV11 and LV12 (Figure L-2) if it is necessary to drain the level of liquid in the base of the tower (refer to Section VI). LV13, LV14, LV15, and LV16 (Figure L-2) should remain closed at all times during stripping operations.

Activate the stripping towers by turning on the two main blowers (B101, B102). Refer to Figure L-2. Starters for both the blowers and well pumps are located on the main control panel. Switch the toggle switch on the left side of the main control panel to the *on* position. This will power the starters and activate the blower for the fixed-bed catalysts. Press the starter buttons for the main blowers. Use the Yokogawa™ controllers on the upper control panel to set the air flow rates at the desired values. For information on operation of the controllers refer to the Yokogawa™ manual in Attachment IV. After the blowers reach steady state (approximately 1 to 2 minutes) turn on the switch for the discharge pump. This switch is located beneath the starter buttons. The three well



pumps (P101, P102, P103) can now be turned on. Refer to Figure L-2. Press the appropriate starters. Set the water flow rates to the desired values using the Yokogawa controllers on the upper control panel.

## **B. BENCH-SCALE CATALYTIC UNITS**

To operate the bench-scale catalytic units, open valves (Refer to Figure L-3) GV5, GV6, GV7, GV8, GV13, GV14, GV15, and GV16. Adjust valves GV5, GV6, GV7, and GV8 to obtain the desired space velocity through the catalyst bed. Use the calibration data in Figure L-5 to convert flow rates to the appropriate rotameter values. The air flow rate can be monitored on the accompanying rotameter. Check to see that valves GV9, GV10, GV11, and GV12 are closed (Figure L-3). They are opened only when collecting air samples.

Activate the fixed-bed incinerators by switching on the preheaters and bed controllers. The temperatures should be increased gradually to allow the catalysts to equilibrate and prevent the catalyst beds from overshooting their setpoints. Generally, allow 15 minutes for every 20°F change in temperature (or as specified by vendor). Note that each of the reactor beds has been equipped with a manual/automatic toggle switch and potentiometer dial. These are located on the lower front face of the control panel. The toggle switch must be in the automatic position for the controllers to properly control bed temperatures. Always make sure that the potentiometer dials are turned all the way down. If they are turned up high enough and the catalyst bed is switched to manual mode, the bed temperature will increase rapidly. This may result in destruction of the catalyst. When the catalysts reach their operating temperature, open valve GV4 and close valve GV3 (Figure L-3). This will allow the contaminated airstream to enter the catalyst beds.

J34-39

## FLOWMETER CALIBRATION DATA

DOCUMENT: . 219

Tube Number: 034-39(G,S,SI,C,I)  
Units: std ml/min

Metering Temperature: 70 deg.F  
Metering Pressure: 14.70 psia

STD. Conditions: 1 atmos @ 70 deg.F  
Accuracy: Standard

## SCALE READINGS AT CENTER OF FLOAT

Float Material:	Glass (G)	Sapphire (S)	Stainless Steel (SI)	Carboloy (C)	Tantalum (I)
Float Density:	2.53 g/ml	3.93 g/ml	8.04 g/ml	14.98 g/ml	16.58 g/ml

A I R	Flow (ml/min)		Flow (ml/min)		Flow (ml/min)		Flow (ml/min)		Flow (ml/min)	
	Scale Readings	Flow	Scale Readings	Flow	Scale Readings	Flow	Scale Readings	Flow	Scale Readings	Flow
150	9229	216	150	11807	150	17430	150	24442	150	25924
140	8625	200	140	11068	140	16287	140	22871	140	24228
130	8014	184	130	10286	130	15194	130	21354	130	22612
120	7344	169	120	9467	120	14057	120	19769	120	20941
110	6680	155	110	8650	110	12944	110	18242	110	19326
100	6051	136	100	7853	100	11814	100	16704	100	17701
90	5414	119	90	7051	90	10607	90	15040	90	15951
80	4832	104	80	6282	80	9462	80	13409	80	14221
70	4228	88	70	5504	70	8307	70	11766	70	12477
60	3628	70	60	4735	60	7156	60	10159	60	10771
50	3006	52	50	3941	50	5977	50	8527	50	9045
40	2322	35	40	3077	40	4732	40	6808	40	7235
30	1628	20	30	2184	30	3454	30	5052	30	5373
20	961	8	20	1323	20	2225	20	3334	20	3570
10	357	3	10	511	10	959	10	1523	10	1650

V A I E R	Flow (ml/min)		Flow (ml/min)		Flow (ml/min)		Flow (ml/min)		Flow (ml/min)	
	Scale Readings	Flow	Scale Readings	Flow	Scale Readings	Flow	Scale Readings	Flow	Scale Readings	Flow
150	216	315	150	522	150	770	150	814	150	814
140	200	293	140	486	140	717	140	762	140	762
130	184	271	130	451	130	666	130	709	130	709
120	169	249	120	413	120	613	120	653	120	653
110	155	226	110	376	110	560	110	597	110	597
100	136	205	100	341	100	508	100	543	100	543
90	119	182	90	305	90	455	90	487	90	487
80	104	161	80	271	80	406	80	433	80	433
70	88	140	70	237	70	356	70	380	70	380
60	70	118	60	203	60	306	60	327	60	327
50	52	96	50	167	50	254	50	272	50	272
40	35	73	40	129	40	199	40	212	40	212
30	20	48	30	89	30	141	30	152	30	152
20	8	26	20	51	20	85	20	93	20	93
10	3	8	10	19	10	32	10	37	10	37

**DAKOTA**  
INSTRUMENTS

INTROLS INC  
1, Monsey, NY 10952 USA

(800) 879-7713  
292 Route 59 Monsey, New York 10952 USA

Model No. 611281

Figure 5. Flowmeter Calibration Data.

### **C. PHOTOCATALYTIC INCINERATOR**

Refer to Attachment III for startup instructions on the photocatalytic incinerator.

### **D. WATER HEATING SYSTEM**

The packing in the towers will need to be cleaned after extended periods of use. This is indicated by increasing pressure drops across the packing as well as decreased removal efficiencies. The towers should be cleaned separately so that the maximum water flow rate can be used for cleaning. To clean out the towers, the air stripping system must be turned off (refer to Section IV.A for shutdown procedure). To clean the countercurrent tower, close valves LV7, LV8, and LV14 (Figure L-2). Open valve LV15. Place the 3-inch high-temperature discharge hose (located at the base of the countercurrent tower) into surge tank T105. Fill the surge tank with 100 gallons of clean water. Refer to Attachment V for operating instructions on the Sioux™ water heater (H101). Activate the heater pump. Allow the level in the surge tank to reach steady state. Turn on the furnace. Clean until the water becomes extremely fouled, shut down and replace with clean water. Repeat until the water becomes clean.

Follow the same procedure to clean the crossflow tower. However, close valves LV7, LV8, and LV13 and open valve LV16.

## SECTION III SYSTEM OPERATION

### A. AIR STRIPPING TOWERS

The air stripping system requires a minimal amount of routine maintenance during operation. The only task that needs to be done on a regular basis is to make up the water treatment chemical tank if a treatment chemical is being used.

There are a variety of physical parameters that should be monitored periodically. These include:

- inlet and outlet water temperatures (°F)
- inlet and outlet air temperatures (°F)
- air and water flow rates (scfm)
- pressure drop across each tower (in H<sub>2</sub>O).

Measure the temperatures and flow rates on the upper control panel. Measure the pressure drops on the Magnahelic™ gauges located inside the trailer on the faces of the towers.

Water samples should be collected periodically for analysis. The inlet water sample is withdrawn from valve LV5 (Figure L-2). The outlet samples are withdrawn from valves LV17 (counter-current) and LV18 (crossflow). Collect the water samples in headspace-free vials. The vials should be immediately sent to the laboratory for analysis. Both inlet and outlet samples are needed to calculate removal efficiency.

Air samples also can be collected and analyzed to provide mass balance and mass transfer data. Swagelok™ fittings with septa have been provided for sample withdrawal. The Swagelok™ nuts and septa can be removed to allow collection via vacuum canisters. Sample port locations are displayed in Figure L-3. The inlet air sample is ambient air and is collected near the blower inlets.

## **B. FIXED-BED INCINERATORS**

Monitor the following fixed-bed physical parameters periodically:

- bed temperature (°F)
- preheater temperature (°F)
- inlet and outlet air temperatures (°F)
- air flow rate.

Read the temperatures on the face of the control panel next to each incinerator. Measure the air flow rate on the rotameter mounted to the bottom of the incinerator. Use the calibration data shown in Figure L-5 to make the necessary conversion.

## **C. PHOTOCATALYTIC INCINERATOR**

Refer to Attachment III for operating instructions for the photocatalytic incinerator.

## **SECTION IV SYSTEM SHUTDOWN**

### **A. SYSTEM SHUTDOWN**

Open valve GV3 and close valve GV4. Begin decreasing temperatures on the fixed-bed incinerators. Decrease the temperatures 20°F every 15 minutes (or as vendor specifies). Follow instructions in Attachment III for shutting down the photocatalytic incinerator. Turn off well pumps (P101, P102, P103). Refer to Figure L-4. If a water treatment chemical is being used, turn off the dosing pump (P104). Wait until the water drains from the towers. Turn off blowers B101 and B102. Turn off submersible pump (P105). After the fixed-bed catalysts have cooled, turn off blower (B103).

## SECTION V TROUBLESHOOTING

Troubleshooting information on individual pieces of equipment can be found in the vendor literature in Attachments III, IV, and V. Table L-1 lists problems and solutions specific to the crossflow air stripping and catalytic oxidation system.

**TABLE L-1. PROBLEMS/SOLUTIONS FOR TROUBLESHOOTING**

Problem	Possible Causes	Solution
Removal efficiency drops	<ul style="list-style-type: none"> <li>• Towers fouled</li> <li>• Air or water flow rate changed</li> </ul>	<ul style="list-style-type: none"> <li>• Clean towers</li> <li>• Check flow rates, adjust if necessary</li> </ul>
No airflow to fixed-beds	<ul style="list-style-type: none"> <li>• Fuji™ blower overheated</li> <li>• Valves GV3 and GV4 are closed</li> </ul>	<ul style="list-style-type: none"> <li>• Turn off Fuji™ blower. Allow to cool. Restart.</li> <li>• Open appropriate valve. Operating the blower with both valves closed can damage the blower.</li> </ul>
Well pumps will not operate	<ul style="list-style-type: none"> <li>• Sump pump overflow</li> <li>• Breaker tripped or loose wiring</li> <li>• Water accumulation in piping to photo-catalytic incinerator</li> </ul>	<ul style="list-style-type: none"> <li>• There is an interlock to prevent the well pumps from operating when the sump pump overflows. Floats on pump may be tangled, preventing the sump pump from activating.</li> <li>• Check breaker and wiring.</li> <li>• Drain water at base of U-piece.</li> </ul>
Fixed-bed heaters shut off	<ul style="list-style-type: none"> <li>• Interlock between blower and heaters activated</li> </ul>	<ul style="list-style-type: none"> <li>• Check to see if Fuji™ blower is operating. If not, turn off switch, allow to cool, and restart.</li> </ul>
Water treatment chemical not delivered to inlet water stream	<ul style="list-style-type: none"> <li>• Dosing pump not primed or significant amount of air in the line</li> </ul>	<ul style="list-style-type: none"> <li>• Prime pump. If there is air in the line between the water treatment chemical tank and the pump, this could cause a change in the amount of treatment chemical delivered to the inlet water. Remove the air by opening valve LV6.</li> </ul>
Furnace in water heater will not ignite	<ul style="list-style-type: none"> <li>• Burner may need to be primed</li> </ul>	<ul style="list-style-type: none"> <li>• Prime burner.</li> </ul>
Cannot decrease water flow rate by changing setpoint on water controller	<ul style="list-style-type: none"> <li>• Too much back pressure in waterline</li> </ul>	<ul style="list-style-type: none"> <li>• Partially close valves LV1, LV2, and LV3.</li> </ul>
Pressure drop across towers increases	<ul style="list-style-type: none"> <li>• Towers are fouled</li> </ul>	<ul style="list-style-type: none"> <li>• Clean towers</li> </ul>

**ATTACHMENT I**  
**STRIPPING TOWER BLUEPRINTS**

(Provided in separate binder.)



**ATTACHMENT II**  
**MAJOR EQUIPMENT LIST**

TABLE II-1. MAJOR EQUIPMENT LIST

Tag Number	Name	Vendor/Specifications/Use
P101/P103	Groundwater Pumps	Pumps of Oklahoma; Model 40S15-5 submersible pumps, 40 gpm at 105-ft head, 1.5-hp motor, 460 V, 3 phase; for pumping groundwater; not included with system.
P104	Chemical Dosing Pump	Cole-Palmer #L-07153-62; chemical dosing diaphragm pump; 115 V, 60 Hz, nominal flow 30 gal/day; for feeding groundwater pretreatment chemical.
P105	Discharge Pump	Grainger; Stock # 39663 Teel Centrifugal pump, 7.5 hp 220/460 V, 3 phase, 60 Hz. TEFC motor, 200 gpm at 80-ft head; for pumping water discharged from the air stripping columns.
C101, T101	Air Stripper/Surge Tank	Hydro Group; 1.5 ft dia × 16 ft packing ht, conventional countercurrent packed bed with 1-inch pall rings, 5.5 ft dia × 3.5 ft ht surge tank of 10 minutes retention time; made of structural aluminum.
C102, T102	Air Stripper/Surge Tank	Hydro Group; 2.0 ft dia. × 16 ft packing ht, crossflow, packed with 1-inch pall rings, 5.5 ft dia. × 3.5 ft ht surge tank of 10 minutes retention time; made of structural aluminum.
K101	Knockout Drum	Battelle-built knockout drum; for removal of condensate from airstream.
B101, B102	Air Blower	Chicago Blower Corporation; Design 53 pressure blower, single-stage centrifugal blower, 3 phase.
B103	Air Blower	Grainger; Stock #5Z187; Fujii™ model VFC303P-5T ring blower, ½ hp, 115 V, 25 scfm at 1.5 psi; for supplying air to the four Battelle-built catalytic incinerators.
T103	Chemical Storage Tank	U.S. Plastics; 165-gal plastic storage tank; for preparation and storage of groundwater pretreatment chemical solution feed.
T104	Chemical Storage Tank	500-gal plastic storage tank with cover; surge tank for effluent water prior to discharge.
T105	Chemical Storage Tank	Cole-Parmer; 100-gal plastic storage tank; surge tank for recycling hot water in tower cleaning system.
T106	Fuel Tank	300-gal fuel tank for either kerosene or diesel; previously rented from Cartanza Oil.
H101	Water Heater	Sioux; Model M-1 Instantaneous Hot Water Heater; 1,000,000 Btu/hr; kerosene or diesel fueled; 460 V, 3 phase; includes fuel and water pump; for in situ cleaning of tower packing.
R101	Catalytic Incinerator	KSE, Inc.; Photocatalytic Oxidation System, Pilot Unit Model, nominal capacity at 50 cfm, 480 V, 3 phase and 120 V, single phase.
R102/R105	Catalytic Incinerator	Tubular packed-bed reactor to be built by Battelle, approximately 1½-inch-diameter by 9-inch-long catalyst bed; equipment includes 115-AC, 2500-W Briskheat tape heater and Thermolyne Model F21120 2-inch tube furnace, 240 AC, single phase, 1300 W; for catalytic oxidation tests.

**ATTACHMENT III**

**KSE PHOTOCATALYTIC INCINERATOR OPERATING MANUAL**

(Provided in separate binder.)

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**ATTACHMENT IV**

**FLOWMETER, CONTROL VALVE LITERATURE, AND CONTROLLER LITERATURE**

(Provided in separate binder.)

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**ATTACHMENT V**

**SIOUX™ WATER HEATER OPERATING MANUAL**

(Provided in separate binder.)

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**ATTACHMENT VI**

**ADDITIONAL PROCESS EQUIPMENT LITERATURE**

(Provided in separate binder.)

MEMO FOR THE RECORD: (7 August 2012) After checking with the contractor, neither the contractor nor the Government have been able to locate copies of those items.